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ADVANCES IN NAVAL ARCHITECTURE
FOR FUTURE SURFACE WARSHIPS

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CANADA

ABSTRACT

This paper is a summary of some possible advances in the naval architecture of fast surface warships, as forecast for a recent NATO Long-Term Scientific Study. The forecasts cover resistance and propulsion, seakeeping, stability and control, materials and structures, and power plants, considering both conventional and unconventional hull types. They do not address any aspect of the combat systems or other outfit installed.

On the basis of these forecasts, the potential of promising types of surface warships is outlined, in so far as this is possible without specifying the function of a ship or its payload. These conclusions reflect a consensus reached by 35 experts from the seven nations participating in the NATO study.

SOMMAIRE

   L'auteur fait un résumé de progrès prévisibles dans la
construction de navires de guerre de surface rapides, dont faisait état
une étude scientifique à long terme menée récemment par l'OTAN. Ces
prévisions touchent la résistance et la propulsion, la tenue à la mer, la
stabilité et le contrôle, les matériaux et les structures, ainsi que les
centrales énergétiques ont trait aux types de navires à coques ordinaires
et spéciales. Elles laissent cependant de côté les divers aspects des
systèmes de combat et l'armement des navires.

   Il souligne, à partir de ces prévisions, les possibilités
qu'offrent certains types prometteurs de navires de guerre de surface,
dans la mesure ou l'on peut en juger sans préciser la fonction ou la
charge utile d'un navire. Ces conclusions sont l'expression d'un
consensus auquel en sont arrivés 35 experts représentant les sept pays qui
participèrent à l'étude de l'OTAN.

Advances in Naval Architecture for Future Surface Warships

by Michael C. Eames, B.Sc., M.Eng.* (Fellow)

SUMMARY: This paper is a summary of some possible advances in the naval architecture of fast warships, as forecast for a recent NATO Long-Term Scientific Study. The forecasts cover resistance and propulsion, seakeeping, stability and control, materials and structures, and power plants, considering both conventional and unconventional hull types. They do not address any aspect of the combat systems or other outfit installed.

On the basis of these forecasts, the potential of promising types of surface warships is outlined, in so far as this is possible without specifying the function of a ship or its payload. These conclusions reflect a consensus reached by 35 experts from the seven nations participating in the NATO study.

1. INTRODUCTION

1.1. Origin

One function of the Defence Research Group of NATO is to conduct Long-Term Scientific Studies in various fields, to forecast the progress which science and technology can be expected to achieve, and to assess the resulting impact on the military art. These studies provide research planners with recommendations for both national and multi-national programmes.

Such a study was completed in 1978 on 'New Technologies Applicable to the Design of High Speed Surface Vessels', and the author was privileged to serve as Study Director. Three objectives were addressed:

(i)   to forecast technological advances contributing to high-speed ship design;

(ii) to define the zones of promise of the various foreseen ship types,

(iii) to recommend priorities for research and development.

The final report of this study represents a remarkable consensus reached by a group of 35 experts from Canada, France, Germany, the Netherlands, Norway, the United Kingdom and the United States. Although the distribution of the final report is limited, most of the forecasts that formed the technological base of the study were derived from information available in the open literature. It is therefore possible to return some of these forecasts to the open literature, and this is being done in the hope that they may serve a wider purpose.

1.2. Scope

Considering vessels that could be operational by the year 2000, Sections 2-5 present forecasts of advances in ship platform technology under headings of,

2   Resistance and Propulsion

3   Seakeeping, Stability and Control

4   Materials and Structure

5   Power Plants.

Section 6 discusses some speculative concepts, for vehicles which may not be operational by 2000, but which offer prospects warranting further research effort. Finally, Section 7 presents general conclusions regarding the relative potential of the various ship types in so far as these can be drawn without specifying the function of a ship and its payload.

Although 'high speed' appears in the title of the NATO study, there was a consensus that improved speed *at sea* is an *objective to be sought* in virtually all warships, except perhaps the largest. The study therefore encompassed all classes of surface warship below 10,000 t. Emphasis was placed on the maintenance of speed in high sea states, not on the attainment of extreme calm-water speed.

1.3. Ship Types

Table I lists the ship types considered, in four categories. Category A comprises types that promise versatile open-ocean capability by the end of the century. Types in Category B may show equal promise, but are speculative as yet. Those in Category C are timely, but are restricted in their versatility by size or other limitations. Finally, Category D covers types that were judged too specialised to warrant detailed investigation in the NATO study.

Except for Section 6, the summary presented in this paper is confined to Category A.

Table I also shows a more fundamental division of types into two generic classes: displacement ships and 'advanced naval vehicles'.

1.3.1. Advanced Naval Vehicles

The term 'advanced naval vehicles' (ANV) is used to cover vehicle types which sustain most of their weight dynamically at their design speed, or by powered aerostatic lift. The various kinds of hydrofoil and air-cushion ships* are the main examples.

The most encompassing aspect of design common to all ANVs is weight consciousness; light weight is essential to their very concept. It has required the use of advanced materials

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*For convenience, this paper follows the USN distinction between an air-cushion vehicle (ACV), which is skirted all round its periphery, and a surface-effect ship (SES), which employs side hulls with flexible seals at bow and stern only.

TABLE I. Types of ships considered

CATEGORY	ADVANCED DISPLACEMENT SHIPS	ADVANCED NAVAL VEHICLES
A	Advanced Destroyer Slender Ship Semi-Planing Ship Small-Waterplane-Area-Twin-Hull Ship (SWATH) Enlarged Ship	Hydrofoil Ship Air Cushion Vehicle (Fully Skirted) Surface-Effect Ship (Side Hulls)

B	Hybrid Concepts
	Finned Slender Ship
		Wing-in-Ground-Effect Vehicle (WIG)
		    both with and without jump
		    capability
		Special Hydrofoil Craft

C		Pure Planing Craft Surface-Piercing Hydrofoil Craft Small Air-Cushion Craft
D	Semi-Submerged and Bulbed Ships Conventional Catamaran	Special Planing Craft Near-Surface Hydrofoil Craft Special Air-Cushion Craft

and led to innovations in structural design. Early ANVs led the way in introducing the aircraft-type gas turbine to the marine environment. Novel transmissions and propulsors have been developed to achieve the high power/weight ratios demanded.

The essential tipping of the design balance towards light weight and high performance, away from redundancy and margins, has led to scepticism about the true operational viability of ANVs. Early examples have often appeared to justify these doubts, but usually because developmental short-comings have been mistaken for fundamental difficulties. Light sub-systems of high operability demand meticulous attention to design detail. Failure to face up to the conse-quent high engineering costs—which admittedly appear pro-hibitive when absorbed by a single prototype—has been the underlying cause of most problems. The question of the cost that can be justified operationally to obtain the higher per-formance of an ANV cannot be answered here.

1.3.2. Advanced Displacement Ships

With buoyancy virtually a free commodity, displacement ships do not have the same motivation for weight conscious-ness. On the other hand, weight reduction to a modified extent is necessary to produce a successful advanced ship, intermediate in performance and cost between the conven-tional warship and the ANV. Such vehicles may well be attractive to the smaller NATO navies, and have not pre-viously received the attention they seem to deserve.

Some designers argue that there is no point in seeking weight reduction because modern displacement warships have become volume limited. This is fallacious because power requirements are still directly dependent on total weight. Weight reduction is more difficult to achieve because of higher structural weight fractions and more exacting stability constraints in volume-limited ships, but it remains important to any attempt at increasing performance.

Moreover, it is not clear that future warships will continue to be volume limited. It can be argued that a peak is being reached in the growth of low-density electronic and weapon systems, and that the future trend will be towards more compact integration and miniaturisation. The inevitable economic trend to smaller complements will also be sig-nificant, because personnel and their facilities are among the largest users of volume.

1.3.3. The Enlarged Ship

A concept opposite to the weight-reduced advanced ship is also worth studying, namely the 'enlarged' ship. Because steel structure is the least costly part of a modern warship, it might make economic sense to seek additional speed and seakeeping ability simply by making the hull very much too
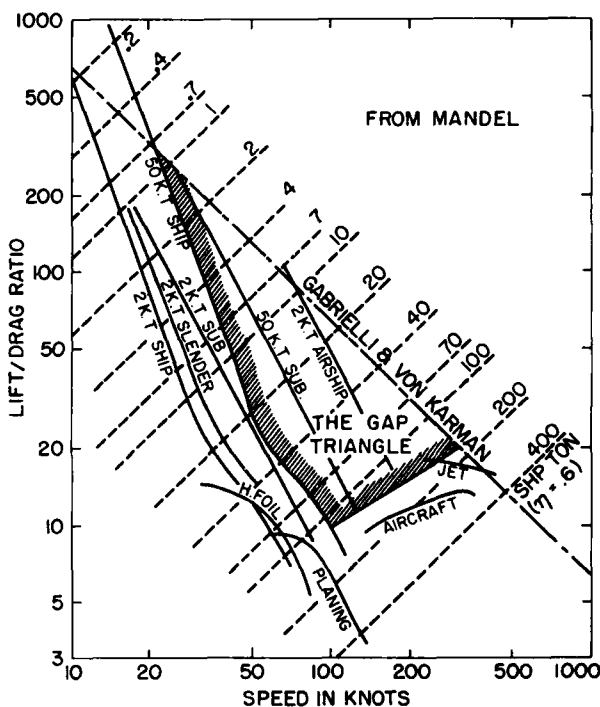

Fig. 1. Lift/Drag Ratio Versus Maximum Speed, (Ref. 1)

large for the payload and outfit it carries. It is vital to this concept to keep the additional hull volume empty except for ballast and fuel, otherwise one merely arrives at a larger and more expensive conventional ship. By installing the payload and crew of a 2500 t ship in a 5000 t hull, however, a more slender form could be used, with increases in struc-tural weight fraction easily absorbed, and offering improved sea speed and ride quality.

At a time when NATO ships are being criticised for not bristling with as many weapons as their counterparts, this concept will be unpopular. Nevertheless, while investigating the result of adding foil systems and air cushions to hulls, one should not overlook the obvious idea of adding more hull. It is worth noting that this approach may be particularly attractive to the concept of modular combat systems, since modules may incur significant penalties in weight and volume, difficult to accommodate in weight-conscious vehicles.

2. RESISTANCE AND PROPULSION

Although calm-water speed is not meaningful for naval operations, limitations on calm-water performance obviously carry through to the real environment, and provide the best point of departure for the study. In 1962, Mandel[1] compared the potential of various novel types of ship. His work brought into focus important general facts about ship performance that will remain valid.

Fig. 1 is Mandel's plot of the lift/drag ratio of vehicles as a function of speed, effectively an update of the classical Gabrielli and von Kármán plot[2]. The following conclusions can be drawn from these data.

(a) For transport efficiency, the comparatively slow and large bulk carrier with lift/drag ratios of 500-1000 has no competition. It is fruitless to seek a high-speed logistics carrier among surface vehicle concepts.

(b) Increases in the speed of marine vehicles stem from increases in their power/displacement ratio, not from improvement in lift/drag ratio. Most merchant ships require less than 1 kW/t compared with 6-15 kW/t for typical warships and 30-80 kW/t for ANVs. The major factor permitting the ANV to achieve this power concentration is the lower specific weight of its propulsion machinery.

(c) Contrary to some popular opinion, the wavemaking resistance of surface ships, which accounts for the hump in the surface-ship curves, does not constitute a 'barrier' to increased speed for displacement ships of suitable form. Hydrofoil power plants in destroyer hulls could produce speeds of 50-60 knots in calm water.

2.1. Resistance

2.1.1. Advanced Displacement Ships

Development of improved long-term anti-fouling coatings or the possible use of copper-nickel alloys will have a practical payoff in the reduction of frictional resistance[3]. Additives and other methods of boundary layer control are unlikely to be worthwhile for routine use in surface warships[4,5,6].

The destroyer form that has evolved over many years will remain hard to beat for a range of speeds up to the primary wave-resistance hump. However, the application of lighter power plants will offer the future designer a wider choice of speed regime. There are four practical alternatives, all of which deserve more intensive study:

(a) to depress the bulk of the volume well below the surface, best typified by the SWATH ship;

(b) to made the ship 'unnecessarily' long, staying well below the primary wave-resistance hump;

(c) to accept near-hump operation, but using a very slender form to reduce its significance;

(d) to design well beyond the hump in the semi-planing regime.

The SWATH form is not well suited to very high speeds because of its large wetted surface; design speeds in the 25-35 knot range are probable. Its wave resistance is sensitive to geometry and compromise is required to obtain good performance at both design and cruise speeds.

The lengthened hull and other slender forms best match the enlarged ship concept with reduced payload ratio. This is because of the increased structural-weight fraction and stability limitations of slender hulls.

Recent developments in planing hull design[7] have demonstrated a promise of much improved seakeeping and lower resistance at off-design speeds. Compared with the classical planing hull, these forms will have high beam loadings, and length-beam ratios of 6 or more.

2.1.2. Hydrofoil Ships

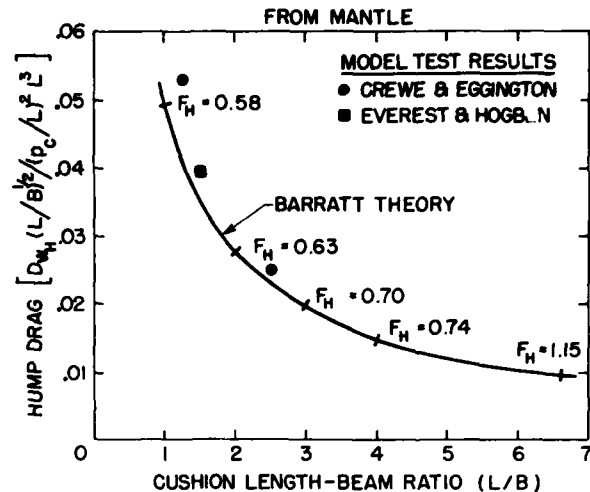Most existing hydrofoil craft have been designed for 'ferry'

Fig. 2. Hump Wave Drag of ACV and SES, (Ref. 12)

missions, with scant attention paid to hullborne characteristics. Future larger hydrofoils will have to operate hullborne at speeds of 15-20 knots, and research is needed to meet the combined requirements of hullborne resistance and seakeeping, take-off trim and resistance, foilborne wave impacts and compatibility with foil configuration. The hull of the FHE-400[8] may represent a good starting point.

Cavitation limits the practical attainable speed of a fully submerged hydrofoil system to 55 knots in calm water and 50 knots in rough water. Surface-piercing systems could be designed for speeds 5-10 knots higher. Cavitation also limits the minimum practical take-off speed to 25-30 knots for fully submerged foils and to 20 knots for surface-piercing foils.

Despite its advantage in foilborne speed range, the surface-piercing foil system is unlikely to prove competitive in craft larger than 300 t because of its higher drag, increased structural weight and inferior ride quality.

The latest seagoing hydrofoil designs have favoured the canard foil configuration with a relatively small bow foil on a single steerable strut[9]. The advantages of this are expected to remain valid for hydrofoil ships up to about 1000 t. Beyond this, design of the steerable bow foil becomes difficult and main foil span becomes unwieldly. A tandem configuration with a two-strut bow foil may be necessary for larger ships[10].

The fully-ventilated supercavitating hydrofoil offers theoretical promise of speeds of 80 knots or more, but with high drag and many practical difficulties. The conflicting requirements of sub- and supercavitating operation have led to the development of a 'mixed foil'[11] which changes its section shape at transition by the use of a flap. Compared with typical subcavitating lift/drag ratios of 15 at 35-40 knots or 12 at 50 knots, such a foil might yield 6 at 80 knots. This would be suitable for sprinting, but probably not for sustained operation. Much research is needed to develop a practical mixed foil design.

2.1.3. SES and ACV

Fig. 2, reproduced from Mantle[12] following Barratt[13], shows the maximum or 'hump' drag coefficient as a function of cushion length/beam ratio (L/B). The Froude number (based on L) at which the hump occurs is shown at points along the plot. This diagram illustrates two alternative trends in SES development to minimise the problem of wave drag.

Virtually all current ACV and high-speed SES designs employ a small L/B, accepting a high hump coefficient, but surmounting it at a Froude number as low as 0·60-0·65, where
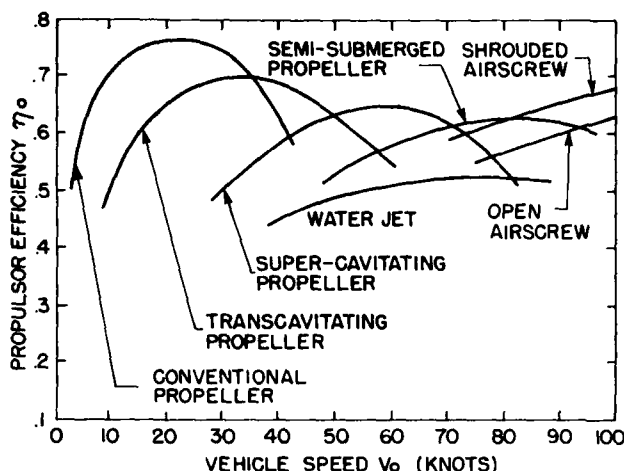
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Fig. 3. Typical Propulsor Efficiency Envelopes

the absolute value of the drag is reasonable. Beyond the hump, wave drag is less for low L/B, and these craft are intended to operate well beyond hump speed at all times.

As vehicle size increases, the alternative concept of operating sub-hump becomes practical. A large L/B of 4-6 is used, greatly reducing the hump coefficient, and shifting it to a Froude number beyond the design speed of the vehicle.

The term 'skirt drag' is used to cover all the retarding forces of friction, spray generation and local impact due to skirts and seals. The problem of estimating this drag is easier with SES because of the smaller seal area. However, the large increase of skirt drag that occurs in rough water is difficult to predict and this, together with a corresponding increase in momentum drag, makes forecasts of the rough-water performance of future ACV and SES somewhat less reliable than those of other vehicles.

2.2 Propulsion

2.2.1. Propulsion Efficiency

Efficiency envelopes for various propulsors are presented in Fig. 3. This shows the maximum likely efficiency at design speed, and it is important to appreciate that a specific design of a propulsor will not achieve its envelope efficiency at any other speed.

In practice, the propulsor efficiency is modified by its operating environment adjacent to the hull and appendages of the vehicle. Hull efficiency varies with the number of propellers employed, their direction of rotation and relative spacing, hull form and appendages. It is not yet possible to predict these effects in general terms. SWATH ships with large diameter, relatively slow turning, deep propellers behind cylindrical submerged hulls have the most favourable propeller-hull interaction.

The concept of hull efficiency does not strictly apply to air propulsors but there are other important installation factors limiting the propulsive coefficient that can be achieved in practice. These include the superstructure wake, cross winds, spray ingestion and propeller wake interference, in addition to the usual geometric limits on diameter.

2.2.2. Propulsor Forecast

For design speeds up to 40 knots, some form of subcavitating propeller is the clear choice. The counter-rotating propeller offers the highest efficiency, but the mechanical complexity of this, or controllable pitch, will have to be justified by

trade-off studies for each specific design. The pump-jet offers good prospects for noise reduction, but incurs penalties both in efficiency and mechanical complexity. There is scope for research into propeller arrangement—tandem, overlap, stators, etc.- to absorb higher powers in limited space without loss, but no major gain in performance can be forecast. Indeed, the conventional propeller is forecast to remain the best compromise for most applications below 40 knots.

The transcavitating propeller[14], although only extending the speed range to 50-55 knots, nevertheless covers an important part of the spectrum of practical rough-water speeds. It is the only high-speed propulsor capable of maintaining good efficiency down to low cruise speeds, obviating the need for secondary propulsion systems for some applications. Its uniquely useful speed range justifies further research into variants of this type.

For design speeds beyond 50 knots, the supercavitating or superventilated propeller is most efficient and lightest in weight[15]. Beyond 70 knots these propellers should operate in the partially-submerged mode in vehicle types where this is practical, because appendage drag begins to become prohibitive. However, the problem of transmitting large powers and the effects of cyclical loading must be overcome before partially-submerged propellers can be recommended for large craft. Water-jets are less efficient and heavier, but they offer a mechanically simpler alternative.

The speed at which air propulsors start to become attractive is hard to forecast. It can vary from 60 to 100 knots, depending on the diameters that can be accommodated in a given vehicle, and the trade-off with underwater appendage drag. Although their airborne noise is very high, air propulsors may well prove advantageous because of lower underwater radiated noise.

2.3 Transport Efficiency

Fig. 4 shows the forecast trends of transport efficiency for all existing types of naval vehicles, at their volumetric Froude number corresponding to maximum calm-water speed. Note that the scale is compressed beyond a transport efficiency of 10. Transport efficiency is defined by:

$$\Omega_0 = 5 \cdot 045 \frac{\Delta V_0}{P_0} \frac{(t)(kt)}{(kW)} = 6 \cdot 878 \frac{\Delta V_0}{P_0} \frac{(ton)(kt)}{(HP)}$$

where Δ is the full-load displacement, and P_0 the shaft power required at maximum calm-water speed, V_0.

In summary, the transport efficiency of high-speed ships in *calm water* can be grossly forecast as follows:

(a) For volumetric Froude numbers from 1 to 2
   1. Displacement Ships   — 50 → 10
   2. SWATH Ships   — 38 → 9

(b) For volumetric Froude numbers from 2 to 3
   1. SES   — 13 → 8
   2. Hydrofoil Ships   — 11 → 8
   3. Semi-planing Ships   — 7 → 5

(c) For volumetric Froude numbers from 3 to 4+
   1. SES   — 11 → 8
   2. Amphibious ACV   — 10 → 6
   3. Small Hydrofoils   — 9 → 7
   4. Planing Craft   — 4 → 3

Table II indicates the volumetric Froude number corresponding to typical speeds and displacements.

TABLE II. Volumetric Froude Numbers

	30 kt	40 kt	50 kt	60 kt	70 kt	80 kt
100 t	2·30	3·06	3·83	4·60	5·36	6·13
500 t	1·75	2·34	2·92	3·51	4·09	4·68
1,000 t	1·56	2·08	2·60	3·12	3·64	4·17
2,000 t	1·39	1·86	2·32	2·78	3·25	3·71
5,000 t	1·19	1·59	1·99	2·39	2·79	3·19
10,000 t	1·06	1·42	1·77	2·13	2·48	2·84

KEY TO DATA POINTS

CONVENTIONAL SHIPS	⊙
SEMI-PLANING SHIPS	⊡
PLANING CRAFT	⬙
SWATH SHIPS	⊡
HYDROFOILS (FIXED FOILS)	▽
(RETRACTABLE)	△
SURFACE EFFECTS SHIPS	⬠
AIR CUSHION VEHICLES	⬠

3. SEAKEEPING, STABILITY AND CONTROL

The behaviour of marine vehicles in rough water is the most fruitful field for future research and the most difficult to forecast. Better methods of predicting and reducing slamming, wetness and motions of displacement ships at high speed are required. No satisfactory theory for predicting ACV motions exists, while more efficient ACV and SES ride control systems need to be developed.

The establishment of universally accepted seakeeping criteria is urgently required. In particular, there is a lack of information on the effects of random motions in 6 degrees of freedom on crew task performance. A more basic approach to buoyancy and stability criteria is also needed to ensure that the potential of advanced vehicles is not limited by inappropriate constraints.

3.1 Sea Speed

Figs. 5, 6 and 7 show the sea speed that can be maintained by various ship types as a function of sea height, for 200, 1000 and 5000 t ships respectively. These represent the trends forecast to be typical in the study time scale, and are based on the most outstanding performance demonstrated to date. The times shown are mission durations; where none is shown, the performance is power-limited and endurance is limited only by fuel consumption.

3.1.2. Advanced Displacement Ships

Further improvements in performance may come from changes in proportions. In particular, a deep draught and high freeboard will alleviate slamming and wetness, and an increase in length will improve ride quality. Further im-
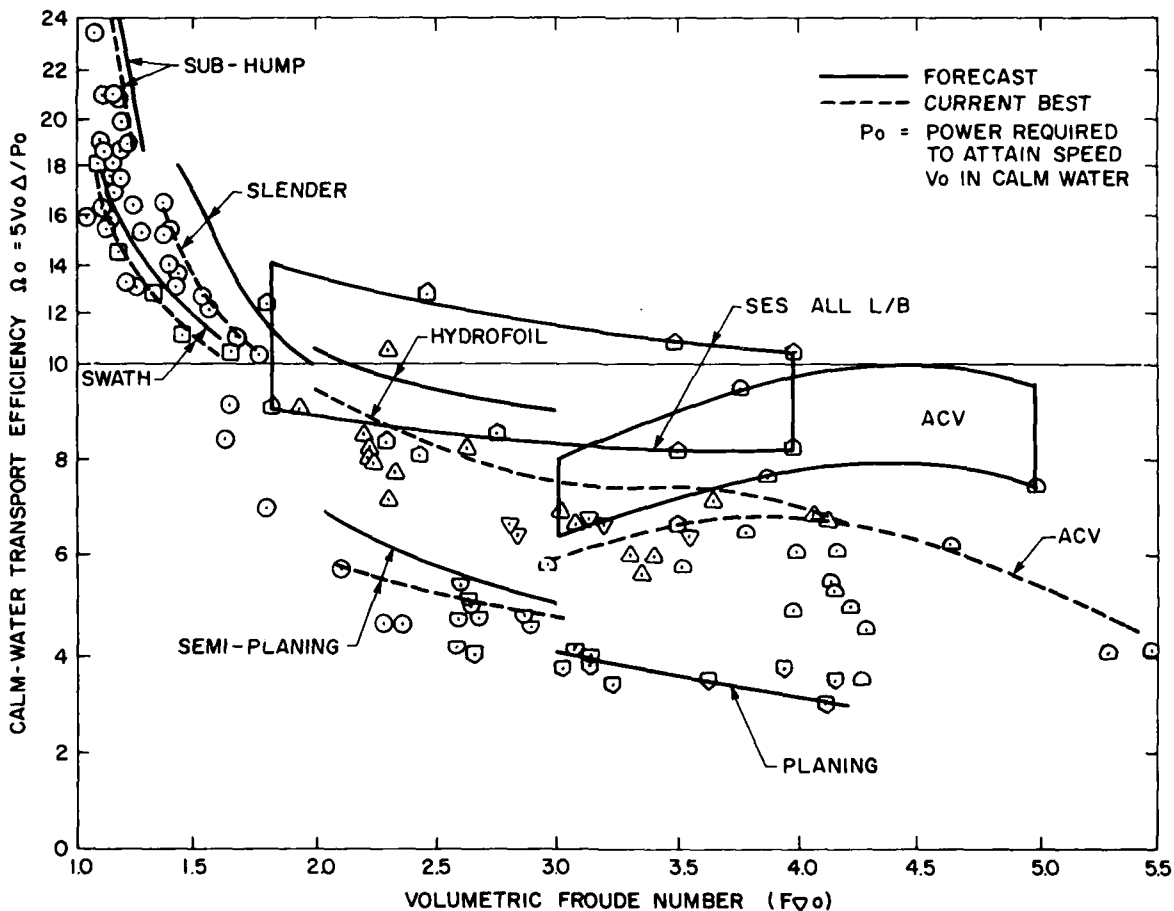

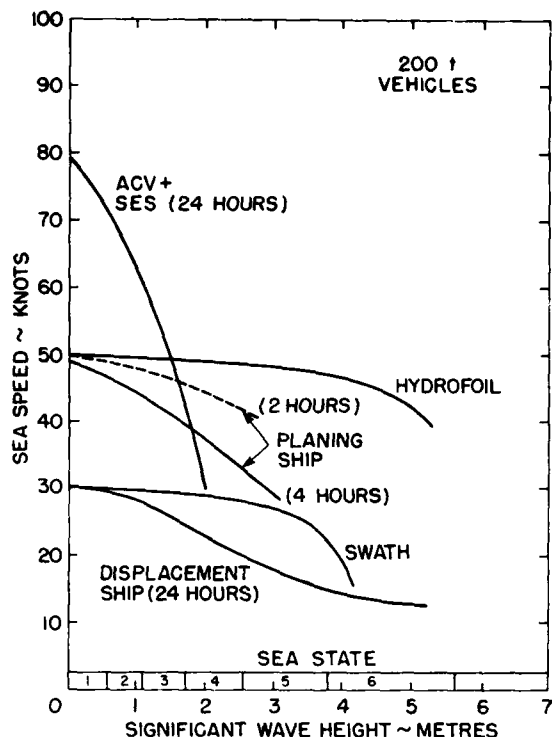Fig. 4. Forecast Trends of Transport Efficiency
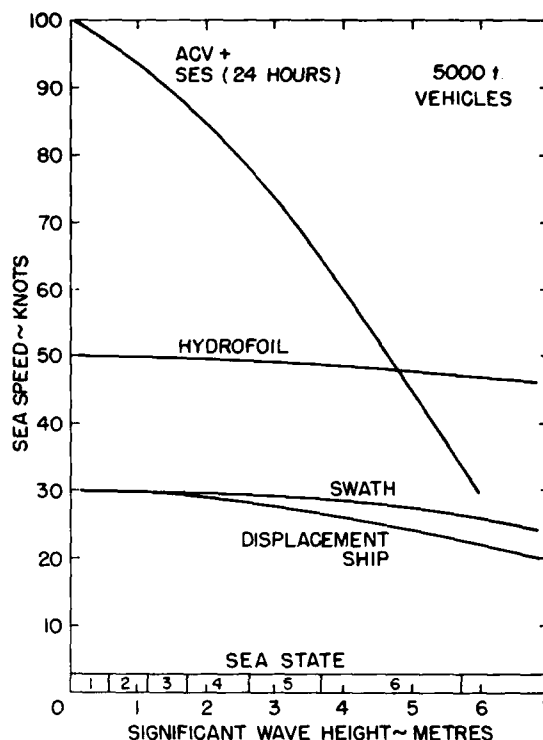
Fig. 5. Maximum Sea Speed of 200 t Ships
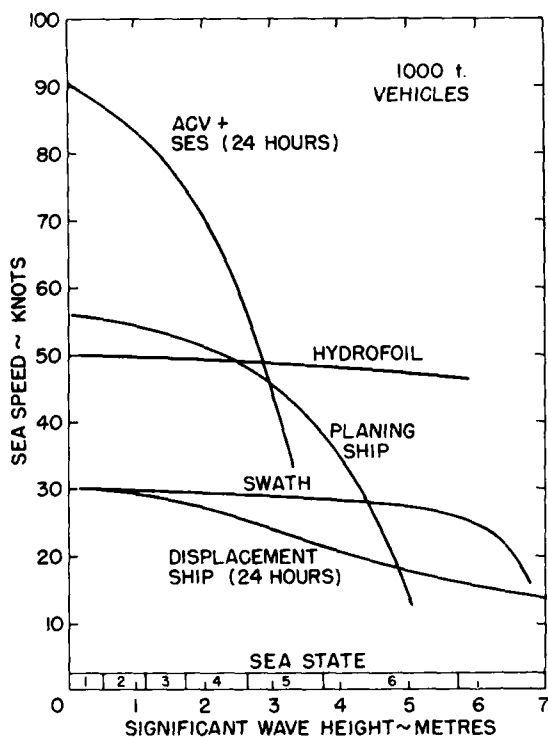

Fig. 7. Maximum Sea Speed of 5000 t Ships

Fig. 6. Maximum Sea Speed of 1000 t Ships

provements in ride quality will be obtained by attention to the distribution of the crew in the ship. These trends will lead to slender and deep ships.

With proper design of damping fins, SWATH ships should be limited only by added resistance up to a sea height at which slamming of the box structure occurs. It appears feasible to provide adequate clearance for sea state 6 in all practical sizes of SWATH ship, i.e. above 2000-3000 t.

The apparently small difference shown in Fig. 7 between SWATH and the conventional ship is misleading in two respects. With the speed loss of a SWATH ship solely due to added resistance, an increase in design speed would yield a corresponding increase in sea speed. However, increased power will not influence the slam or motion limited speed of a displacement ship. Moreover, the ride quality of the SWATH at its limiting speed will be significantly better.

3.1.3. Advanced Naval Vehicles

Below 1000 t, the hydrofoil is the only vehicle capable of sustained high speeds in rough seas. Moreover, with fully-submerged foils, speeds above 40 knots can be maintained in sea state 6 down to the smallest sizes of hydrofoil likely to be operationally useful. Above 1000 t, hydrofoils continue to hold the advantage in seakeeping, but may require more sophisticated control systems.

Planing ship designs up to 1000 t, based on new concepts[7], also promise high speeds for exposure times consistent with their short-duration missions in moderate seas.

Small ACV and SES suffer severe speed loss in moderate and high sea states, but high speed over rough water may be achieved by increasing size and installed power.

3.2 Static Stability and Safety Measures

All naval vehicles must meet certain standards of reserve buoyancy and stability, both intact and when damaged and partially flooded. The standards set for conventional ships have become so entrenched that there is a tendency to lose sight of their arbitrary nature, and to regard any new vehicle as unsatisfactory if it fails to meet them. In this respect the USN deserves congratulations for its initial formulation of standards specifically for advanced vehicles[16].

Nevertheless, studies to seek a rational basis for stability and damage-control standards are required. Problems are already being encountered, for example, by hydrofoils with retractable foils. Since seagoing operations are not sensible with foils retracted, it appears unreasonable to impose full stability standards on this condition.

Because of their inherent breadth, ACV and SES have good ultimate reserves, but once their hard structure is afloat, they are restricted in mobility. SWATH ships have the additional problem of large initial angles of heel, caused by flooding one hull with very little reserve buoyancy in the struts. Counterflooding will almost certainly be required.

The slender deep ship will require special attention to meet conventional standards, and the question arises whether powered and dynamic means of achieving stability will become acceptable for naval vehicles. It is relatively simple to stabilise dynamically against roll and beam winds, if forward speed of the ship can be used. With the development of robust inflatable structures and the availability of large quantities of air or exhaust gas, auxiliary sponsons could be used when stopped.

3.3 Dynamic Stability and Control

3.3.1. Roll Stabilisation

A conventional hull provides low damping of roll, and methods of increasing this are usually, although erroneously, called 'stabilisation'. Hydrofoil technology can be expected to lead to more efficient designs of stabilising fins.

An interesting new concept is to combine the functions of fins and rudders to provide integrated control of roll and yaw. At moderate speeds, the existing rudders of a warship could give roll reductions comparable to those of existing fins, but at high speeds, amplification of rolling motions can occur at low frequencies.

There are broader implications for the future; new forms of control surfaces are likely to be developed to combine rudder and fin functions more efficiently and with reduced noise. Another concept that should be studied is stabilisation by controlling the transverse movement of a weight; surprisingly small weights may be effective.

In semi-planing ships, control surfaces may provide a true stabilising function, because the expected hull forms lose stability at high speeds. Research is needed to resolve the advantages of hard-chines in this regard, but control augmentation will probably be desirable, and will follow hydrofoil technology.

More extensive application of dynamic stability augmentation will depend on the constraints imposed by safety standards, as discussed above. However, there is no doubt that stability governs the design of most modern warships, often dictating hull-form features undesirable for both resistance and seakeeping. Research into means of augmenting stability could have important long-term payoff, even if its immediate exploitation appears limited by today's safety and damage control criteria.

3.3.2. Pitch Damping

The most obvious application of anti-pitching fins is to improve the motions of SWATH ships in quartering and following seas. This is an important aspect of SWATH design requiring further study.

Despite disappointing early experience in applying such fins to conventional ships, recent experience with hullborne hydrofoil ships has demonstrated a potential for much improved motions. The 200 t FHE-400, for example, has cruised at 12 knots in 7·5 m (25 ft) seas with motions comparable to those of an accompanying 3000 t frigate[17]. Further developments are therefore possible; in particular, the combination of bow fins and anti-rolling fins on a slender hull, as suggested in Section 6.

3.3.3. Hydrofoil System Control

Current technology is well proven and adequate for craft up to 500 t, but problems will arise with increasing size, demanding further research and development on fully-submerged foil systems. Several factors lead to the need for relatively larger control forces with increasing vehicle size. Improved flap-effectiveness from refined section design is expected to meet these needs in ships up to 1000-1500 t. However, studies of alternative lift-control devices, such as full incidence control, tabs, detached flaps or leading-edge flaps, may reveal better solutions, and these complexities may be unavoidable in very large sizes.

Minimisation of control power and linkage loads is important in studying these alternatives, because there is a distinct danger of exceeding the state of the hydraulics art. This would result in very high development costs.

The steering and directional control of large hydrofoil ships with tandem foil configurations will introduce a new series of design problems. Avoidance of strut ventilation in turns is perhaps the topic deserving highest priority among these, if large hydrofoil ships are to retain the outstanding manoeuvrability of their smaller sisters.

3.3.4. Air Cushion System Control

After intensive effort, a fundamental understanding of the stability and control of ACV and SES is beginning to be achieved, but no best method of achieving pitch or roll stability has emerged. The ACV uses various skirt configurations to set up pressure differences within the cushion, either by compartmentation or by skirt deflection. For SES, the sidehulls and seals are designed to produce the required roll restoring moment; adequate pitch stability is also obtained by careful sidehull and seal design.

Cushion pressure relief by venting is the principle employed by first-generation ride-control systems, but this can demand the installation of up to 50% additional lift power. Active fan systems, controlling inflow rather than outflow, are already being built, and the development of a good ride control system is seen as the key to ACV SES employment in the open ocean.

On ACVs, aerodynamic surfaces are often employed for directional stability, but if the craft must head along its course without sideslip, dynamic control is required from air propulsor systems.

The directional stability problem for SES has more similarity to conventional ships than to ACVs. In the multi-thousand-tonne size, directional control is obtained by underwater fins. As in the case of conventional ships, it may be acceptable for the SES to be moderately statically unstable as long as it is dynamically stable.

4. MATERIALS AND STRUCTURE

The importance of high power/weight ratio to the performance of any naval vehicle has been shown, and the largest single component of weight is the vehicle's structure. With modern techniques of structural analysis, design for minimum weight would be straightforward if the applied loads were known accurately and the long-term properties of materials under load in sea water were reliable. Unfortunately, neither is true and it is in these two areas that future effort is mainly required.

A more nebulous problem for the forecaster arises from the high cost of strong materials and light structures. Depending on the weight sensitivity of the vehicle type, different standards of weight reduction will be economically justifiable, and detailed design studies are needed to assess the trade-off reliably.

4.1 Materials

Mild steel, high tensile steel, and alloys of the HY80 type will continue to be the preferred materials for marine vehicles wherever their use does not significantly restrict vehicle

performance. High-strength steels (HY130) are likely to be used in special applications only. Continued study directed at improving their fatigue and corrosion resistance in these special applications is required.

The use of aluminium alloys in future ships will expand. For weight-sensitive ANVs, extensive use of this material is mandatory. Continued study of the long-term durability of aluminium alloys is required, including fatigue and crack growth. Fire protection of aluminium alloys is of paramount importance for the future development of high-speed vehicles. Selection and development of candidate thermal-protection systems is required[18].

The use of titanium alloys for small components such as high-speed propeller blades and possibly for strut/foil systems will expand, but cost is likely to prohibit their emergence as primary structural material within the time scale of this study.

The low modulus of elasticity of glass-reinforced plastic precludes its broad application in high-performance vehicles. No general application as a main structural material is foreseen for vessels longer than 20 m. However, applications to hulls requiring non-magnetic properties will continue, and increased use can be expected in superstructures, especially where complex shapes are required.

Advanced composite materials, using carbon or boron fibres to achieve acceptable moduli, show great promise for special components of high-performance vehicles. External appendages requiring mouldability and involving minimal fire risk are leading candidates for these very strong but costly materials[19].

Development efforts to improve flexible skirt materials and, in particular, to understand failure mechanisms and the effects of extreme environmental conditions should continue as a matter of urgency[20]. The life expectancy and maintenance costs of existing flexible skirts continue to be a major concern when contemplating high speeds and larger sizes.

4.2 Structural Loads

4.2.1. *Displacement Ships*

Traditional methods are gradually giving way to probabilistic methods of predicting ship response and loads in a seaway. This is unlikely to decrease the structural weight of conventional ships significantly because highly efficient designs have evolved from long experience. Ironically there is a rather large amount of model and full-scale data, which could be used to validate new methods, but exploitation of these data has not been a priority. There will continue to be a strong need for full-scale seakeeping trials measuring motions, loads and the seaway simultaneously.

For small ships, the practical minimum thickness of steel plating dictates hull weight to a major extent. This is not the case for aluminium ships, except for the smallest of the vehicles under consideration. Semi-planing ships larger than 200 t are beyond the range of empirical methods and data now used for smaller fast craft[21,22].

4.2.2. *ACV/SES Structure*

In the absence of theory and the uncertainty of scaling, much reliance is placed on loading criteria developed by the UK Civil Aviation Authority from accumulated operational experience with hovercraft[23]. However, the UK vehicles fall within a narrow band of low cushion pressures, and the application of these criteria to radically different designs is questionable.

The implication of this empirical state-of-the-art is that it is not possible to forecast the structural weight of future large ACV or SES. Although advocates of the large SES have published curves showing a steady reduction of structural weight fraction with size, other authorities have shown a rising trend. Which is correct depends upon the assumed trends of cushion power, drag, motions and loads.

4.2.3. *Hydrofoil Systems*

Since cavitation limits the lift that a foil can generate, estimating the maximum hydrodynamic loads on foil systems is comparatively straightforward. The largest piece of debris that a foil can strike without damage must be determined. This can be much larger than the debris a hull could safely strike at the same speed, a point not commonly appreciated.

Further work is required to establish the likely lifetime spectrum of load fluctuation for proper design to fatigue limits. It is much more difficult to predict typical operating loads in a seaway than to predict the maximum loads.

These comments apply to subcavitating foils. Not enough is known to attempt quantitative load predictions for super-cavitating foil systems.

4.2.4. *Survival and Combat-Related Loads*

There is a tendency to assume that cushionborne or foilborne loads will always exceed those encountered at hullborne speeds. However, the large ANV must be designed to ride out a severe storm at sea, involving large impact loads on superstructure and deck installations. This can be achieved within acceptable weight penalties, but limits may well be imposed on the size and proportions of superstructures.

As a minimum, protection must be provided against a 'cheap kill'. Unfortunately, there is a general lack of experience in the compromise that will be involved in designing larger weight-sensitive vehicles against the loads of underwater shock and air blast.

4.3 Structural Design

4.3.1. *Large Hulls*

For conventional displacement ships above 1000 t, in which longitudinal bending dominates the design, steel will remain the preferred material. Fabrication difficulties and costs will militate strongly against grades stronger than HTS, and mild steel will continue to be used for many components.

The motive for weight reduction is stronger for SWATH ships because of the larger area of plating, under comparatively moderate loading. Current design studies have included mixed material construction, in which the lower hulls, struts and lower half of the box are of HTS, with aluminium used for the upper half of the box and the superstructure. In practice, all-steel construction will be preferred unless payload requirements necessitate the weight savings associated with mixed material or even all-aluminium construction.

4.3.2. *High-Speed Hulls*

Although the trade-offs are complex, and should be carefully studied for each case, aluminium construction will probably be justified whenever wave impact loads dominate the design.

For semi-planing ships, maximum loads will be more accurately predicted and the substantial factors of safety now used can be reduced. In keeping with their intermediate sophistication, economics will dictate compromises in structural design for ease of manufacture. This is forecast to result in a structural weight 60% that of the equivalent steel structure, rising to 75% if full passive fire protection is required.

In contrast, the hulls of hydrofoil ships are already being designed to the limits of weight saving, achieving 45% of the equivalent steel structure. Here, future improvements are expected to be directed at reducing the high cost of maintaining this level of weight.

4.3.3. *ACV/SES Structures*

Little can be forecast except that these will be among the least dense of surface vehicles, with large areas of flat surfaces, making it more difficult to achieve low structural weight fractions. Their large flat surfaces will allow them to take advantage of aluminium honeycomb and other sandwich types of structural components without incurring prohibitive costs. Inevitably, however, their structural cost will be high.
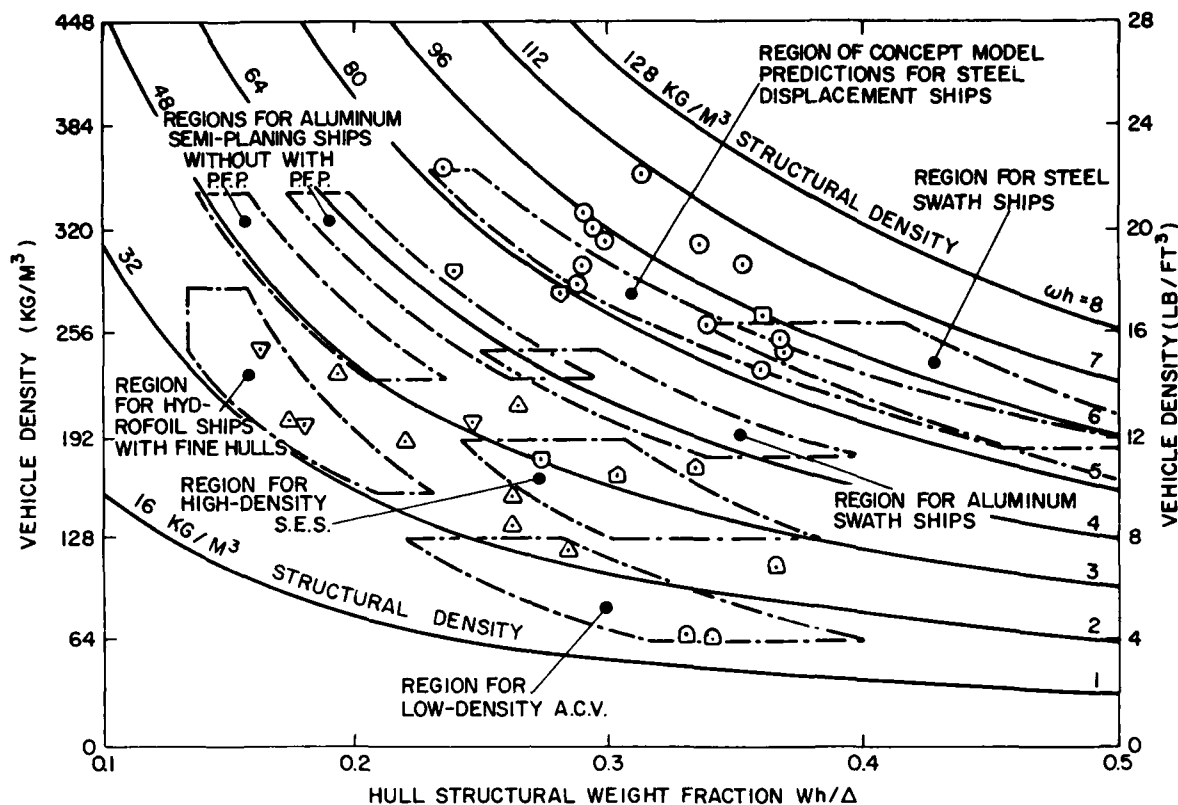
Fig. 8. Vehicle Density as a Function of Structural Weight Fraction

4.3.4. Hydrofoil Systems

In the near future, HY-130 or a steel of equivalent strength will be used, with later possibilities of HY-180, titanium or graphite composites. Only composites with a high Young's modulus will be acceptable, so that their future for this application is difficult to forecast. However, a good composite would lower foil-system weight substantially.

4.4 Structural Weight Forecast

Although scantlings of primary structural components are determined by the loads imposed on the vehicle, the extent of the structure, and hence the majority of its weight, depends upon the volume that has to be enclosed. Vehicle density plays a vital part in determining the structural weight of a vehicle[24], as shown convincingly in Fig. 8.

In this plot of vehicle density (total weight/total enclosed volume) against hull structural-weight fraction (hull structure weight/total weight), data for existing vehicles cluster according to type, along lines of constant structural density (hull structure weight/total enclosed volume). While it is not possible to forecast hull structural weight fractions, therefore, the structural densities shown in Table III should be generally applicable.

TABLE III. Forecast Structural Density

	lb/ft^3	kg/m^3
Conventional ships –Steel	5–6	80–96
SWATH ships–Steel	5·5–6·5	88–104
SWATH ships–Aluminium	3·5–4·5	56–72
Semi-planing ships–Aluminium	3–4	48–64
Hydrofoil ships–Aluminium	2–3	32–48
SES–High cushion density	2·5–3·5	40–56
ACV–Low cushion density	1·5–2·5	24–40

5. POWER PLANTS

Readers may be surprised to find no discussion below of possible alternative power plants using unconventional fuels. This is because earlier NATO studies had concluded that warships smaller than 8-10,000 t would continue to use liquid hydro-carbons throughout the time frame of the study.

The selection of power plant for a high-speed vehicle is primarily governed by the need to achieve high power/weight ratio. In addition to fuel economy and total weight of machinery and fuel, other important requirements are simplicity, low maintenance and high availability.

5.1 Gas Turbines

Current and foreseen improvements in the fuel consumption of marinised simple-cycle gas turbines will make these a clear choice for main engines. In most ships, combined plants will be adopted, with small gas turbines or high-speed diesels chosen for cruise engines, depending on particular requirements. The case for all-gas-turbine ships will increase with time.

TABLE IV. Typical Gas Turbines of the 1990s

Design Power		Spec. Fuel Consumption	
kW	SHP	kg/kW hr	lb/SHP hr
~4,500	<6,000	0·30	0·49
7,500	10,000	0·275	0·45
15,000	20.000	0·25	0·41
30,000	40,000	0·225	0·37
60,000	80,000	0·20	0·33

Gas turbines will be available up to 60,000 kW (80,000 SHP) by 1990, with specific fuel consumption as low as 0·20 kg/kW hr (0·33 lb/SHP hr). Consumption at part power and

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air-flow rates will also be significantly improved. Further gains will come with the introduction of ceramic hot-sections[25], but such engines are unlikely to be sufficiently well proven by 1990 and have not been assumed for performance estimates of ships operational in 2000. Typical engines likely to be available are as shown in Table IV.

There are numerous other types of gas turbine engines, designed to improve upon the efficiency of the simple Brayton cycle. Intercooling, reheating, heat recovered from the exhaust, either for use within the cycle or for generating steam in a combined gas-steam plant; all combinations of these have been proposed or are being investigated. Theoretical advantages notwithstanding, the practical problems associated with complicating the simple cycle in any way act as a severe dampener to enthusiasm, even at this early, somewhat academic stage. The attraction of the gas turbine as a marine power plant lies in its fundamental simplicity.

However, there is a special exception in the case of the closed-cycle gas turbine[26] because of its long-term potential for light nuclear power plants, teamed with a high-temperature gas-cooled reactor. Continued research in this field is to be encouraged.

5.2 Diesel Engines

With typical installation weights of 45-90 kg/kW (75-150 lb/SHP), directly coupled low-speed diesel engines cannot be considered for high-speed ships. Even medium-speed geared diesel installations in the 15-30 kg/kW (25-50 lb/SHP) range, employed in some low-powered frigates, are too heavy for serious consideration. Their noise and vibration characteristics are also a disadvantage for most naval applications. It is possible that the largest high-speed ships may use medium-speed diesels as cruise engines, but more likely that they will employ small gas turbines.

Small high-speed diesels, with installation weights of 6-12 kg/kW (10-20 lb/SHP), will continue to be used in the less sophisticated fast patrol craft, where patrol time dominates, and as cruise engines in some larger ships. Their good specific fuel consumption will improve to about 0.20 kg/kW hr (0.33 lb/SHP hr) for design powers over 1500 kW (2000 SHP). Engines are available up to 7500 kW (10,000 SHP), but gas turbines will almost certainly be the practical choice for higher unit power. High maintenance effort is a current disadvantage of high-speed diesel engines, and an important target for future development.

5.3 Steam Plants

Steam plants have reached a high degree of development and it is unlikely that future refinements will be significant enough to introduce new advantages over the gas turbine for high-speed vessels. Specific fuel consumption is unlikely to be improved below 0.25 kg/kW hr (0.41 lb/SHP hr) for high-power steam plants weighing 12-15 kg/kW (20-25 lb/SHP).

With future pressure-fired boilers, installation weight might be reduced to 9 kg/kW (15 lb/SHP), but only with intensive effort[27]. There is little incentive for this development for high-speed vehicles, in view of the higher maintenance, manning and space requirements of steam plants.

The current advantages of steam plants are their better economy at part power, their reversing capability, smaller intake and exhaust volumes, low exhaust temperatures and their ability to burn a wide variety of hydrocarbon fuels. These will continue to justify careful examination of the relative merits of steam and gas for all naval vessels of moderate power[28].

5.4 Combined Plants

The usual large difference in power requirements between design speed and cruise speed, coupled with the rising specific fuel consumption of gas turbines at lower power, strongly suggests the use of multiple engines.
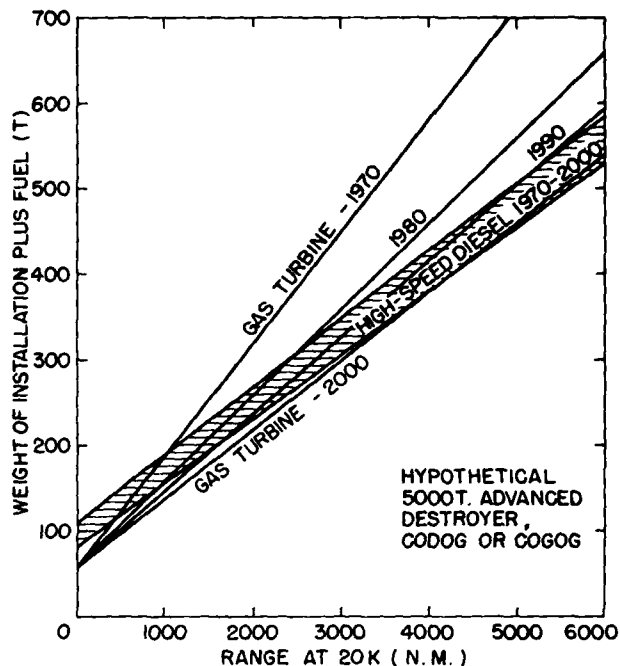

Fig. 9. Cruise Engine Selection Trends

The simplest solution is to employ a multi-shaft installation, closing down the engines not needed. In most design situations, this calls for a larger number of smaller engines than desirable for economy at high speeds, so that a compromise is involved. However, it has the merits of simplicity and standardisation, and will find application in the smaller sizes of weight-sensitive craft.

The addition of coupled smaller gas turbines for crusing is one of the current choices of high-speed ships, operated in COGOG configuration. There are indications of a trend towards higher intermediate speeds suggesting the adoption of COGAG with four equal power engines in a two-shaft arrangement. The choice between COGOG and COGAG configurations will depend on how the required powers are matched to available engines.

As noted above, the alternative use of high-speed diesels for cruise engines should always be explored, because of their better economy. However, the economy of gas turbines is improving more rapidly and future trade-offs may be very different. This is demonstrated in Fig. 9, which shows the total weight of cruise-engine installation plus fuel, as a function of range at 20 knots, for a typical 5000 t destroyer. Four separate gas turbines are compared, representing 1970, 1980, 1990 and 2000 technology, against a band showing the corresponding anticipated development in high-speed diesels.

With the gap closing at this rapid rate, future selection is unlikely to be determined simply by weight; other factors will over-ride small differences. The added complexities of combined steam and gas turbine plants are similarly not expected to show compensating advantages.

5.5 Transmission

A large fraction of power-plant weight is devoted to reduction gears, shafting and bearings, and there is scope for much improvement based on technology developed for heavy-lift helicopters and similar vehicles. Straightforward adoption of such technology is as inappropriate as the use of an aircraft engine in a ship, but a break with the heavy machinery tradition of marine engineering is needed; the marinised gas turbine well demonstrates the blending of technologies required.
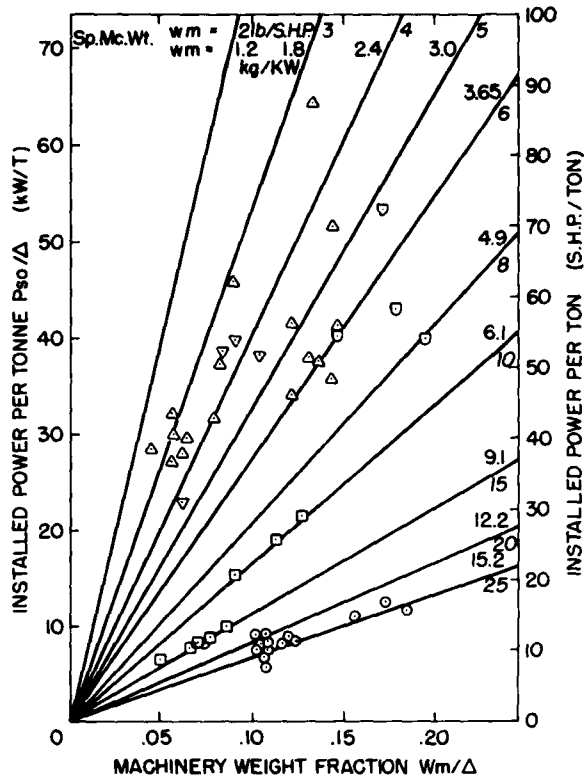
Fig. 10. Power Displacement Ratio as a Function of Machinery Weight Fraction

Hydrofoil, ACV and SES prototypes have already sponsored such engineering effort for reliable right-angled drive transmissions, but further development is needed to increase transmitted horsepower and to reduce the technical risks inherent in this type of drive. Long-term experience at sea is lacking, and difficult to obtain with prototype vehicles. Extensive use of land-based test sites is essential for this and many other aspects of machinery development.

Despite the advantage of flexibility, electric and fluid drive systems have not been used in high-speed craft because of their weight. Superconducting electrical machinery offers new and attractive prospects for weight and volume reduction, with the flexibility of using any number of engines remote from the propulsion shafts, and the possible elimination of separate generators for auxiliary power. Because all these factors are involved, the potential benefits vary widely between vehicle types and sizes, and no quantitative general forecast can be made. It is clear that further development and application studies should be encouraged. Accelerated development will be necessary for proven systems to be available for ships to be operational by 2000.

5.6 Machinery Weight Forecast

Fig. 10 shows the relationship between power/displacement ratio and the machinery weight fraction, with lines of specific machinery weight. Machinery weight includes all components of the propulsion plant, but excludes the electrical generating plant and other auxiliaries. The data clustering close to the 15·2 kg/kW (25 lb/SHP) line are for steam plants of recent warships. Early gas turbine installations show only a small reduction.

Without compromising design standards or undertaking ambitious development programmes, gas turbine plants are predicted to reach a specific weight of 8·5 kg/kW (14 lb/SHP) within the time scale of the study. By undertaking specific

programmes, a further reduction to 6·1 kg/kW (10 lb/SHP) is forecast to be achievable without compromising 'big ship' qualities.

Corresponding forecasts for smaller craft powered by gas turbines are given in Table V.

TABLE V. Specific Machinery Weight Small Ships

	lb SHP	kg kW
Semi-planing ships	7	4·3
Hydrofoil ships Retractable foils	4·5	2·7
- Fixed foils	3·5	2·1
SES (Water propellers)	3·3	2
ACV (Airscrews)	2·5	1·5

6. SPECULATIVE VEHICLE CONCEPTS

A great variety of special vehicles was examined during the NATO study; various types of semi-submerged ships and catamarans[1], special planing craft such as sea-sleds and the 'Sea Knife', and many configurations of hydrofoil and air cushion craft. In general, such types offer a single and specific advantage at the expense of all-round capability. Their development for naval use will depend on the establishment of a military role requiring the particular advantage.

There are, however, two generic classes of vehicles, as yet speculative, that could find broad naval application beyond 2000. These are the hybrid concepts and WIG vehicles (Wing-in-Ground-Effect).

6.1 Hybrid Concepts

Hydrofoil ships, hovercraft and conventional ships use dynamic lift, powered static lift and buoyancy, respectively, to support their weight. As defined here, a hybrid vehicle is one which embodies more than one of these sources of sustension over a major portion of its operating regime.

Fig. 11, taken from Jewell[29], illustrates his 'sustension triangle' for defining hybrids. A vehicle is defined by three integers (x, y, z), whose values represent to the nearest tenth the fraction of weight supported by buoyancy (x), dynamic lift (y), and powered static lift (z). Thus 'pure' displacement, hydrofoil and air cushion ships are represented at the x, y, z vertices of the triangle, respectively.

The examples now being studied by the USN all lie along the sides of the triangle; early work suggests that the engineering complexity of combining all three means of support is unlikely to prove worthwhile. This is not a firm conclusion; indeed the whole field of hybrids requires and deserves further study.

6.1.1. Air Cushion Hybrids

Because an air cushion profoundly dictates the geometry and structure of the hull, it seems likely that these hybrids will always use the cushion as their primary means of support, lying close to the z vertex. Such vehicles will usually be intended for the higher speed ranges.

The addition of some buoyancy can improve stability and control, but there will be a severe resistance penalty at high speed. The purist could argue that an SES is a hybrid; indeed it is likely that buoyancy will only be added to an SES for some specific purpose, such as housing propulsion systems.

On the other hand, small secondary hydrofoils added to an air cushion have potential for improving the seakeeping, stability and control of an SES or ACV. The concept should be studied in this context, as part of a research programme for ride control of SES and ACV, not as a new type of hybrid vehicle.
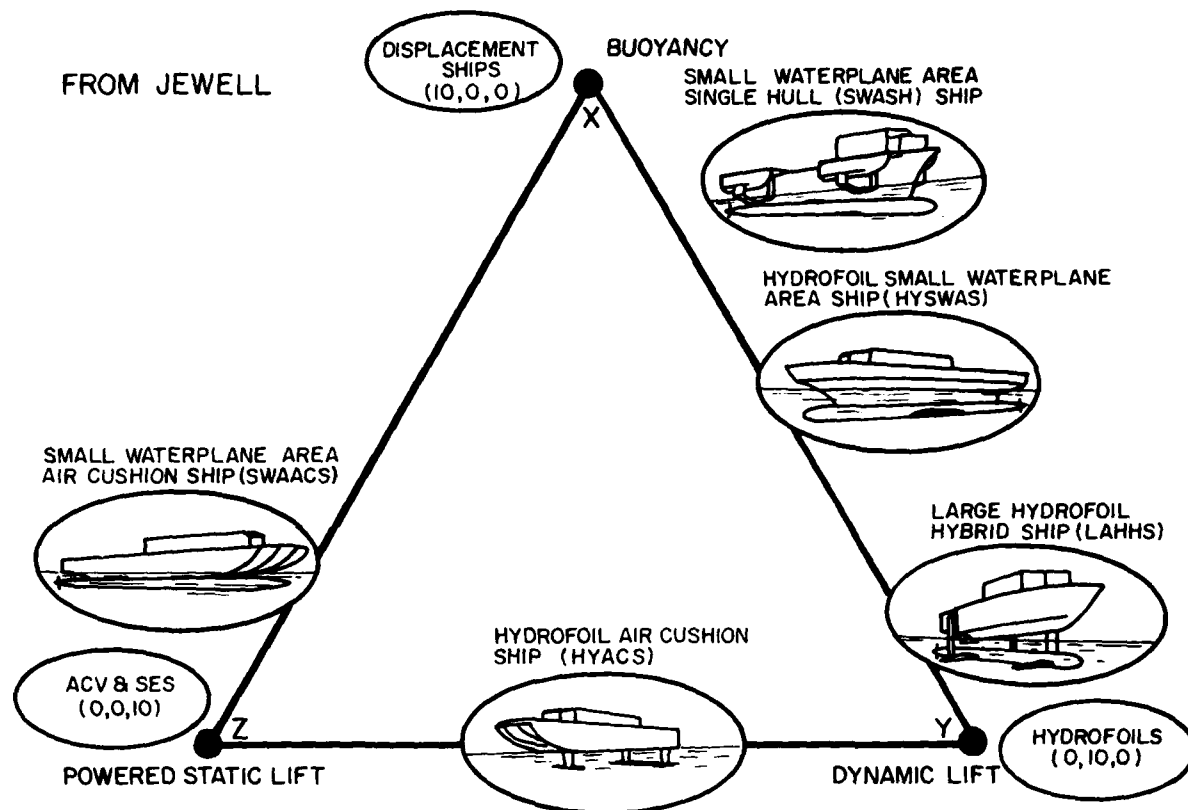
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Fig. 11. Sustension Triangle with USN Hybrid Concepts, (Ref. 29)

6.1.2. Buoyancy-Hydrofoil Hybrids

A wide range of buoyancy-hydrofoil combinations shows potential for increasing the sea speed of displacement ships, or the practical size limits of pure hydrofoil ships. The early USN studies have indicated that these hybrids will be most promising towards the middle of the range of combinations, say from (7,3,0) to (3,7,0), in contrast to air cushion hybrids. Thus a hydrofoil hybrid is likely to evolve, not as a displacement ship or hydrofoil ship with minor appendages, but as a distinctly new ship concept[30].

However, studies to date have been confined to concepts where buoyancy is provided in the form of a single, small waterplane-area hull. Other hybrids can be obtained by using conventional hulls to provide buoyancy, and in many respects these lead to concepts which, if less efficient, are also less complex.

At the buoyancy end, one can envisage slender hulls with enlarged damping fins, used primarily for stability and control, but supplying enough dynamic lift to optimise draught and trim. At the hydrofoil end, one can envisage a ship that is supported just above the calm water surface, but cresting the waves in rough water.

The whole field of hybrid vehicles requires further study before firm conclusions can be drawn regarding their future potential.

6.2 WIG Vehicles

A WIG vehicle is essentially an aircraft that flies very close to the surface to achieve a reduction of induced drag and an increased pressure on the lower side of the wing. The increased efficiency resulting from this ground-effect potentially places the WIG vehicle in the 'gap triangle' of performance (Fig. 1) that cannot be approached by other surface vehicles.

Although 'Jane's Fighting Ships' reports an experimental Russian 'ekranoplan' 120 m long with an estimated speed of 300 knots and a capacity of 900 troops, the NATO study was forced to conclude that technology has not yet reached the stage when quantitative characteristics can be forecast for operational vehicles.

However, two types of WIG vehicles appear to have unique operational potential, justifying further research:

> Type A, with sizes greater than 1000 t, cruising always in ground-effect at speeds of 200-300 knots.

> Type B, with sizes between 50 and 500 t, normally cruising in ground-effect at speeds of 150-200 knots, but with the capability of flying out of ground-effect for short periods.

Typical concepts are shown in Fig. 12. The third, Type C, is a concept outside the scope of surface vehicles; an aircraft employing WIG technology only for take-off and landing.

The sketch of the Type B vehicle shows a small German prototype which is part of an active development programme being conducted by the Rhein-Flugzeubau company, following the pioneering work of Lippisch[31]. Research in WIG technology is also active in the US[32].

7. SUMMARY OF PROMISING CONCEPTS

Although the technology forecasts of the NATO study encompassed a wide range of possible vehicles, comparative studies were restricted to those which:

(a) have demonstrated promise for open-ocean operation in a range of sizes offering operational versatility;

(b) could be developed in time to enter operational service by 2000.
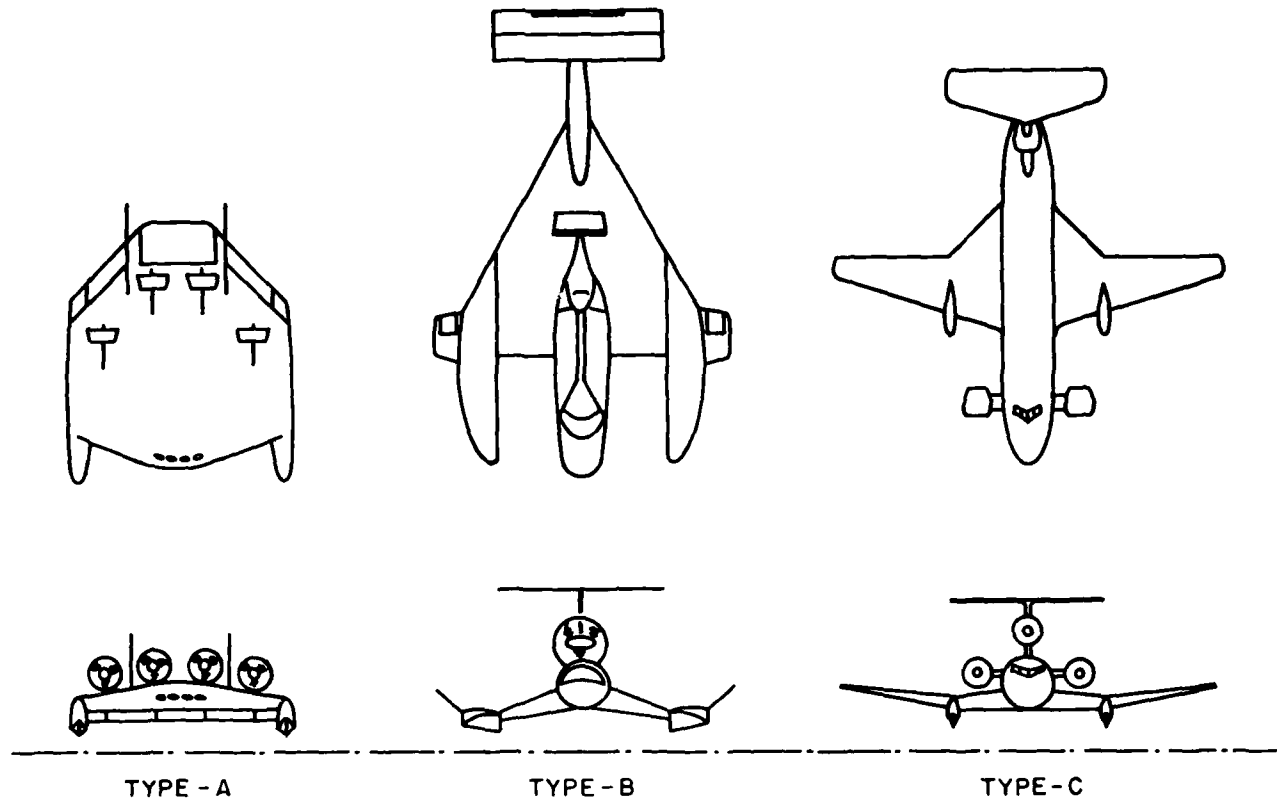
TYPE - A   TYPE - B   TYPE - C

Fig. 12. Wing-In-Ground-Effect Vehicles

Mathematical models were developed to compare the performance and cost of these promising vehicle types on the basis of a consistent set of objective assumptions. Without the function or payload being defined, these models are confined to platform parameters such as transport efficiency, useful load, range, sea speed, and relative platform cost. They do not include all the measures of effectiveness which will be required to select the best vehicle once a specific operational objective has been defined.

Moreover, there are many qualities of the platform that cannot be reduced to simple measures; survivability, dependability, versatility, technical risk and other operational features. These were assessed qualitatively, relative to the known capabilities of conventional displacement warships.

The following sub-sections summarise the potential of each main vehicle type, as concluded from both the quantitative and qualitative comparisons. This summary reflects the consensus of the 35 study participants.

7.1 Advanced Displacement Ships

Single-hull displacement ships have potential for design speeds up to 40 knots in sea state 4, although their speed losses in higher seas vary with type and size. They represent the future standards against which the other vehicles should be compared, and their applications cover the roles of present fast patrol boats, frigates, destroyers and cruisers.

The two main areas in which significant performance gains can be realised are the improvement of seakeeping through hull-form research to raise sea speeds, and the increase of power/displacement ratio through weight reduction of machinery, outfit and possibly structure. Hull-form optimisation for seakeeping is the more important if sea speeds are to be maintained in sensible proportion to calm-water speeds, and useful-load ratios held consistent with volume constraints.

The idea of an 'unnecessarily' large hull is worth exploring further. In principle, it is just as valid to add more hull to a hull, as it is to add hydrofoil systems or air cushions.

The addition of more extensive damping and control fins to a displacement hull is a field that could be rewarding. The finned slender ship, while purely speculative at present, represents a new class of semi-sophisticated ships that could evolve by taking ideas and technology developed for advanced naval vehicles, and applying them to improve the performance of larger conventional ships.

7.2 SWATH Ships

In calm water the SWATH ship offers no speed advantage over other displacement forms; indeed its resistance is likely to remain higher, particularly at low patrol speed. Current optimum design speeds of about 30 knots may increase somewhat, but not beyond 40 knots.

Nevertheless, the SWATH's outstanding ability to maintain speed in all but freak sea conditions, with excellent ride quality, makes it a promising concept in the 30-40 knot speed range. The combination of these seakeeping qualities with an inherently large and high deck makes the SWATH a natural concept for naval aviation.

A large structural weight fraction makes it difficult to provide adequate payload in small SWATH ships. Sizes under 5000 t will probably require all-aluminium construction to achieve high payload fractions. SWATH will show to best advantage in the 10,000-15,000 t class.

The SWATH ship rates with other advanced displacement ships in overall weight sensitivity, platform cost and technical risk. However, the very small reserve of buoyancy in the struts makes it sensitive to changes in weight, and mid-life additions must be pre-planned.

By incorporating the advantages inherent in the small waterplane principle, the SWATH ship has superseded conventional

catamarans for most purposes. It is considered to be the only multi-hull concept with high development potential.

7.3 Hydrofoil Ships

Subcavitating hydrofoil ships will continue to be limited to maximum practical continuous speeds of about 50 knots, regardless of size.

Its outstanding ability to maintain speed in all but freak sea conditions, with excellent ride quality, makes the hydrofoil one of the most promising concepts in the 35-50 knot range. In particular, sizes as small as 300 t will maintain speeds in sea state 6 within 2 to 3 knots of their design speed, making it the only small craft capable of matching the speed and seakeeping of large ships. Together with the SWATH, the hydrofoil ship in the hullborne mode (with foils extended) has seakeeping characteristics better than those of displacement ships at slow patrol speeds. This combination of qualities at high and low speeds makes it the most versatile small ship for open ocean operations.

However, it is an expensive vehicle, and should therefore be developed to exploit its unique capability at small sizes.

Hydrofoil ships will be able to achieve good useful load fraction up to sizes of at least 2500 t. Beyond this, extrapolation is not reliable enough to set definite limits, but disproportionate growth of the foil system is expected to reduce their useful load fraction. The technical risk also increases with size. For these reasons the case for large hydrofoil ships is not so strong; they do not exploit the unique and fundamental advantage of the hydrofoil principle in offering large-warship qualities at patrol-craft sizes.

Relatively high weight and drag, and the rougher ride of surface-piercing hydrofoils, make these unlikely to compete for open-ocean operations beyond 300 tons, but small craft may find naval applications. The number of commercial hydrofoils of this type now in successful operation as ferries attests to the cost-effectiveness of these less sophisticated craft.

Fully ventilated supercavitating hydrofoils offer the possibility of speeds of 70 knots or more, but with high drag, and only after extensive research and development.

7.4 Air-Cushion Vehicles and Surface-Effect Ships

The ACV has the highest potential calm-water speed of any type considered except WIG with the SES running second because of drag and cavitation ventilation problems of its side-hulls. However, high speeds with acceptable ride quality cannot be realised in sea state 6 until multi-thousand ton sizes are reached. The sea speed of both ACV and SES is more sensitive to sea state and vehicle size than in any other type.

There is scope for development of ride-control systems, upon which the future of ocean-going ACV and SES may depend. Establishing a fundamental understanding of cushion dynamics in a seaway, upon which to base control system development, is an urgent need.

The ACV should be developed to exploit its unique amphibious capability, as already begun with riverine warfare craft, assult landing craft and mine-countermeasures craft. This last application exploits differing aspects of the ACV's separation from the water; resistance to underwater shock, low noise, pressure and magnetic signatures. Small ACVs are being used commercially in the Canadian North, and larger over-ice vehicles are expected to be among the next generation of multi-hundred ton sizes.

Among the ships which can be constructed in large sizes, only the SES offers calm-water speeds in the 80 knot range. Although ACVs can be built in large sizes, the limitations of air propulsion and low cushion pressure point towards ships in the 1000 t, 100 knot range as the largest likely to have amphibious capability. In contrast, the potential of the SES

lies in sizes greater than 3000 t, and the USN has taken the significant step of initiating development of a 3000 t prototype.

7.5 Summary of Special Operational Features

The special operational features possessed by the advanced ship types are summarised below:

SWATH:

(1) Excellent platform steadiness and deck arrangements for helicopter and V/STOL aircraft in sizes smaller than normal carriers.

(2) Good characteristics and layout for handling small assault craft or underwater equipment requiring a central well.

(3) Requires deep draught for its size.

Planing:

(1) Least costly way of achieving moderately high speed in moderately rough water, dependent on size.

(2) Completely compatible with established shore facilities for berthing, docking, etc., with relatively shallow draught.

Hydrofoil:

(1) Outstanding seakeeping ability and steadiness at high speed for its size.

(2) Outstanding behaviour at low patrol speeds for its size, particularly appropriate for sustained 'sprint and drift'.

(3) Most manoeuvrable of high-speed surface vehicles.

(4) Requires deep draught for its size, unless foils are retractable.

ACV:

(1) Unique amphibious capability if air-propelled which also reduces waterborne noise and gives high resistance to underwater shock.

(2) Highest potential speed in relatively sheltered waters, but large sizes required for open-ocean capability.

(3) Not suited to low-speed patrol operations.

(4) Precise manoeuvring at high speed is difficult with amphibious type.

SES:

(1) Large potential for increasing size, for speeds greater than 40 knots.

(2) Second highest potential speed in relatively sheltered waters, but large sizes required for open-ocean capability.

(3) Not well suited to low-speed patrol operations.

(4) Good cushionborne reaction time.

8. CONCLUDING REMARKS

An overall conclusion is that the science of high-speed ships is well ahead of its exploitation. A wealth of research lies waiting to be converted into practical design tools, and the emphasis must be on engineering development to achieve clear demonstrations of operational capability, reliability and economic viability.

Traditionally, naval architecture has emphasised resistance and propulsion, but the further gains to be made here are small. The most rewarding field for future research is seakeeping, involving all aspects of the behaviour of vehicles in rough water. Significant gains in sea speed and ride quality are possible in most vehicle types, and some urgent challenges have been identified. Prediction of the forces on vehicles in rough water is also the major factor in efficient structural design.

Beyond the limits imposed by rough water and cavitation, power per ton determines performance, and weight reduction is the second most rewarding field for effort. This is a matter of engineering refinement, which is costly, and it demands careful judgement of a balanced design. Undue refinement can lead to calm-water performance senselessly far beyond rough-water limits.

In many ways this study has confirmed the success of evolution; extrapolation of the conventional destroyer, with moderate weight reduction, results in a platform cost-effectiveness that is hard to beat. Vigorous research into advanced displacement ships is well justified. One displacement variant is the SWATH ship, which shows outstanding promise for air-capable ships of moderate size.

To be economically competitive, the advanced naval vehicles will have to exploit their unique or special operational features. Thus hydrofoils should be matched to roles that demand excellent seakeeping qualities in small ships, at both high and low speeds. ACVs, on the other hand, should exploit their unique amphibious capability, and their highest speed potential over relatively flat surfaces, such as new sea ice.

Of all the speculative and special concepts examined, the wing-in-ground-effect vehicle and buoyancy-hydrofoil hybrids are believed to offer the most promise, both on technical grounds and because they occupy important gaps in the size-speed spectrum.

No single type of vehicle will prove to be universally superior. Each has different performance characteristics which will vary in importance according to the tasks to be performed and the military payload to be carried.

ACKNOWLEDGEMENTS

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DISCUSSION

Mr B. N. Baxter, M.Sc., Ph.D. (Fellow): I am very pleased to open the discussion on this paper. I have known the author for more than 30 years and have followed his career and read his other papers with great interest.

The Institution is fortunate indeed to have a paper of this calibre to whet the appetites of those Naval Architects, particularly the younger ones, who may be somewhat despondent when they ponder the fact that the warships they now see will in many cases still be here in the year 2,000 and think that there surely must be something more outstanding than these conventional hulls.

Most design staffs are so busy solving present day problems that they have little time to try and forecast, in depth, the type and style of future surface warships, particularly in the long-term and for that reason, if for no other, the present paper is very welcome.

If the warship is considered simply as a gun or missile platform then advances in its technology can be considered under the four headings given by the author, i.e.

    Resistance and Propulsion

    Seakeeping, Stability and Control

    Materials and Structure

    Power Plants.

The author states that traditionally resistance and propulsion has been emphasised by naval architects and this is certainly true for those naval architects working in experimental tanks. Naval architects in design offices are still more interested in the outcome of these experiments i.e. the speed associated with a maximum power.

The author appears to stress the speed requirement of 40 knots and I wonder if he sees this value as the dividing line between conventional and unconventional ships?

Materials and structural design are, in general, more important in the shipyards since it is the combination of these that provide the basis of an efficient platform construction and the design criteria used will be judged by success or failure in service. New designs will have to achieve minimum hull weight coupled with an ability to withstand high stresses although the solution to the problems of production-kindly designs is growing more urgent.

Does the author believe that aluminium will be widely used in future warships or is there the possibility of other materials being used instead of steel?

The study of seakeeping and control offers the most profitable sphere of advancement and recent RINA papers have

stressed the harmful effects on the physical well-being and morale of shipboard personnel caused by erratic, aggravated or excessive ship motions. Even partial solutions to these problems would represent a striking advance.

The power plants will, in general, be either COGOG or CODOG and the author states that the case for all gas turbine ships will increase with time. I think that the advantages of CODOG installations would increase as the price of fuel increases and I would welcome the author's views on this.

The categorisation of Advanced Displacement Ships and Advanced Naval Vehicles together with their operational features is extremely useful and should be a guide to future designers bearing in mind that they reflect a consensus of opinion reached by 35 experts. One other extremely useful section of the paper deals with priorities for research and development, and companies as well as research establishments will have to choose carefully those areas where the required advances in performance fit most closely with their own facilities and design abilities.

The author states in his summary that the effects of the installation of combat systems or other outfits are not included in his considerations, but the influence of new weapons on a new design is of paramount importance and therefore it is difficult to consider some of the advanced ship types separately from the weapons they carry, since in many cases the size of the ship is determined by those weapons.

If this aspect is ignored, new designs may result in a ship carrying as many weapons as possible rather than a ship which carries all the weapons required to answer a particular threat.

Whilst the use of micro techniques has meant a significant reduction in the size of equipment required to carry out a specific function within a weapon system, the increased computing power now available has enabled an order increase to take place in the range and depth of functions performed. Further, the application of these techniques to counter-measure equipment has produced a step demand in weapon system sophistication. Thus, despite the improvements in technology, the size and weight of equipment required to be carried is not declining and the number of antennae is increasing.

It follows that the limited payload abilities of most Advanced Naval Vehicles will restrict their use by the blue water NATO Navies since their operational performance is constrained by this limitation. The enlarged ship on the other hand is a most desirable option from the Ship Weapon Systems Engineer's point of view, allowing reduction of mutual interference by improved separation of antennae, reduction in the Radhaz problem, again due to the ease of physical separation and ease of installation of equipment in even modestly enlarged compartments.

Additional cabling due to greater separation will not be a very significant weight consideration since, in future vessels, the use of multiplexing will effect a major reduction in the amount of cabling.

However, it has been traditional for ship costs to be considered as directly proportional to displacement and there is no doubt that ruthless project management will be necessary to prevent the addition of a host of desirable, but not essential items, to any ship which is increased in size.

We have been analysing a detailed cost breakdown, for a private conventional warship design, with a view to establishing the relative costs and performance of incorporating a specific weapons pay load into hulls of differing displacement. This work is not yet complete.

However, if it is assumed that the total cost of labour and material for hull and domestic services accounts for approximately 30% of the total cost, a 20% increase in the displacement and volume should not add more than about 6% to the total ship cost.

Mr D. K. Brown, M.Eng., R.C.N.C. (Fellow): The author has provided us with a magnificent amount of data on the technology of advanced naval vehicles. However, this aspect is rarely the difficult one. The major problems are: What is it for? How much will it cost, both in money and in design and production resources?

Both these questions are difficult to answer and it is both easier and more exciting to concentrate on the technology. In considering the role of advanced naval vessels it is important to remember that the conventional monohull is rarely optimised for either speed or seakeeping, suggesting that the customers. Naval Staffs, do not place a high value on these attributes. It is also important to remember that very few warships are designed for a single role; for example, an A/S frigate may be involved in fishery protection, as guard boat for regattas, goodwill visits, and rescue work both for ships and aircraft.

Is it possible for the author to give some indication of the relative cost per tonne of these various craft and perhaps of the magnitude of design effort which might be involved?

Turning to some more detailed points, I wonder if the emphasis on light weight necessarily applies to the SWATH. It is weight sensitive and its weight must be calculated precisely because of the effect on draught, but this applies equally to a submarine built of thick steel. A steel SWATH will be bigger than one of aluminium for the same payload but if it is cheaper the size does not usually matter.

The possible use of copper nickel alloys for anti-fouling use, raised in Section 2.1.1, seems contrary to the author's light weight philosophy. Is it visualised that the shell should be of this material or of steel clad with thin sheets?

I suggest that the author has put both the minimum size (2000 tonnes) and most likely size (10,000-15,000) of the SWATH too high. The greatest advantage of the SWATH is in seakeeping whose importance is greatest in small ships. Some very tentative studies for an offshore patrol vessel suggested that a SWATH of 1300-1500 tonnes was practical with a 5-metre platform clearance but about twice the cost of the conventional alternative. Conventional ships of 10,000-15,000 tonnes are rarely sea state limited and I believe that the SWATH is more likely in the 5-6,000 range.

I am surprised that Figs. 5, 6 and 7 show identical speeds for ACV and SES. I would expect that the sidewall Hovercraft, to use Sir Christopher Cockerell's chosen name, would equate more towards the performance of a slender conventional ship and the limited data which I have seen tends to confirm this.

I think that the paper needs a glossary of terms, symbols and suffices used. The interpretation of lift/drag ratio is not always consistent between authors and the way in which it is used here should be stated. This addition will then make this paper one of the most useful reference papers available for the advanced warship designer.

Professor D. Faulkner, B.Sc., Ph.D., R.C.N.C. (Fellow): I think this is a first-class paper. I make no excuse for concentrating on the structural side, because in Section 4 the author rightly says that the largest single component of weight is the vehicle structure.

I want to take up a point concerning displacement ships on which I think I would appear to disagree with the author, and no doubt with many others. In Section 4.2.1 he has suggested that because of the feedback of successful experience we have now reached an optimum in the distribution of structural weight. The 1979 RINA paper by Mr Sadden and myself[33] suggested that with more rational methods of structural design it can be shown that even in ships which are designed under the certifying rules, there is a wide scatter of real strength and safety. As far as naval ships are concerned, there is an equally wide scatter. The one thing that is fairly constant in destroyer type naval ships is the proportion of structural weight to displacement, which i. roughly 0·25.

My main message really is that in naval ships the great range can be accounted for because designers who are not bound by any Lloyd's rules or any other classification rules, can design from a wide range of strength, safety and weight distributions for differing compromises with economy. Weight and cost are the two completely conflicting variables in most structures. I believe that many naval designers are consciously sacrificing, if you like, structural efficiency to try to achieve a cheaper hull.

The second point is really related to this, namely, that when you turn to large merchant ships with closed decks, such as big tankers, I believe there is considerable scope for weight saving because of advances in modern knowledge about loading and other uncertainties. This was debated at the ISSC in Hamburg in 1973 and there is much evidence now to support the argument.

The author says in Section 4.3.2 that for high-speed hulls, for semi-planing hulls, maximum loads will be more accurately predicted and the substantial factors of safety now used can be reduced. I thoroughly agree with this. I think you have greater freedom in a thing like a high-speed hull which, in a sense, is not so hidebound by rules, to actually use modern knowledge to reduce safety factors without necessarily jeopardising the safety of the ship or leading to a less reliable vehicle. One of the difficulties of rules is that they can stultify progress, and I am really going back to my first point by saying that I think there is scope for actually taking greater knowledge of loading etc to improve the design of current displacement hulls. The real problem is the compromise with economy, and there is to my knowledge still no satisfactory data bank to which a designer may refer. That still remains one of the very vexed problems in optimised ship structures, and it was debated at the ISSC in Paris last year.

I should like to ask one question. In Section 4.3.4, dealing with hydrofoils, the author makes some terse remarks about the use of composites, including graphite composites, and says that only those with a high Young's modulus would be acceptable. I imagine this must be because of the possibility of hydroelastic excitation and flutter, and I would ask him whether he would confirm this, for example from any knowledge he may have of seagoing experiments or trials in which flutter has been definitely observed.

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Mr K. R. Suhrbier, Dipl.Ing. (Fellow): My comments refer mainly to the section on propulsion, in particular the data given for high-speed propellers in Fig. 3 'Typical Propulsive Efficiency Envelopes'.

Newton-Rader propellers, referred to in the paper as *trans-cavitating propellers*, have been designed and used for a number of Vosper and Vosper Thornycroft craft as well as other high-speed boats. Although we agree with the principal statements made, our conclusions regarding efficiencies and suitable application of this propeller type differ somewhat from those of the author. I would therefore like to make the following points:

(i) The fairly drastic reduction in efficiency shown for the 50 to 60 knot range is not supported by our data (earlier and more recent). It seems that too high cavitation loadings have been assumed, presumably to ensure fully cavitating conditions. Better efficiencies can be achieved (without erosion problems) as indicated in Fig. 13, where some data based on trials and model tests have been added (the hatched area indicates the efficiency range for lighter loadings). More or less constant efficiencies should be expected in the higher speed range, linking up with the curve given for supercavitating propellers. Also, we would not hesitate to

use these propellers up to, say, 60 to 70 knots, and with some modifications maybe even higher.

(ii) The large fall-off of the same curve at low speeds would only apply for conditions for which a design of this type would not normally be considered. Such low values might be obtained in special applications, i.e. high loadings, but they could not be regarded as *typical* or *maximum likely*.

(iii) I am somewhat at odds with the expression *transcavitating propeller*. The word *transcavitating* does not describe a hydrodynamic phenomenon. The fact that these propellers (as some others) operate reasonably well in partially cavitating conditions does not mean that they cannot or do not work in the supercavitating range, too. (Their relevant geometric features, i.e. cambers of the important sections, are very similar to those of other SC propellers.)

(iv) One could also argue about the curve given for supercavitating propellers at 30 to 50 knots. I presume it represents the envelope for the condition at which all sections are fully cavitating. It is, however, not unusual to employ quite satisfactorily propellers with SC sections in less ideal conditions and achieve higher efficiencies than shown. I think it would therefore be more practical to present the *maximum likely* efficiencies of fully submerged high-speed propellers in one curve rather than two.

Furthermore, I was quite interested in the author's discussion of dynamic roll stability of high-speed craft and the suggestion to use control surfaces to overcome stability losses at high speeds. Also, the data given for maximum sea speeds for various types of ships and sizes (Figs. 5 to 7) are certainly most informative and deserve our attention. The hydrofoils speeds seem somewhat optimistic--if they are meant for some duration. I fully agree with the author's arguments for the 'enlarged ship' concept. The addition of more hull is a simple and probably the cheapest way to impr ve the seakeeping and habitability characteristics of a ship, in particular as it also allows accommodation and

working spaces to be arranged in areas of more comfortable motions.

Finally, I would like to express my appreciation for this most interesting and valuable paper.

Mr R. 1. Jackson, M.Sc., R.C.N.C. (Member): I am particularly glad to be here today as I had the pleasure of meeting Mr Eames and some of his colleagues at DREA last year.

I wish to congratulate the author on a very clear, concise and interesting paper concerned with that area of naval architecture which could be characterised as the 'art of the extreme'.

I would like to raise a question concerning the unavoidable link between the performance features of advanced naval vehicles and ships, and their operational worth. Although this aspect is outside the defined scope of the author's paper, I think this is a pity as it leads to some extent to a divergent solution, calling as he says for a 'wealth of research'.

Research and development have to be part of a coherent programme which must include a general evaluation of all vehicles in the context of the whole background of naval warfare, whereby certain appropriate roles are identified, and particular vehicle types are optimised for those roles. The enthusiastic advocate of a new vehicle has to show that it fulfils a role more cheaply or better than the current 'conventional' vehicle. If he cannot, he is wasting his time—a point pursued by O'Neil in a deceptively lighthearted article entitled 'Advanced Naval Vehicles: Who Needs Them?'[34].

A good enough example of what I mean is provided by the author where he says that the case for large hydrofoil ships is not too strong. I know of one design study (not from DREA!) for such a vehicle with a displacement of over 2,000 tonnes. It boasts variable geometry foils, it is apparently capable of speeds approaching 80 knots, and it must qualify for a prize for the most costly way of taking two large helicopters to sea.
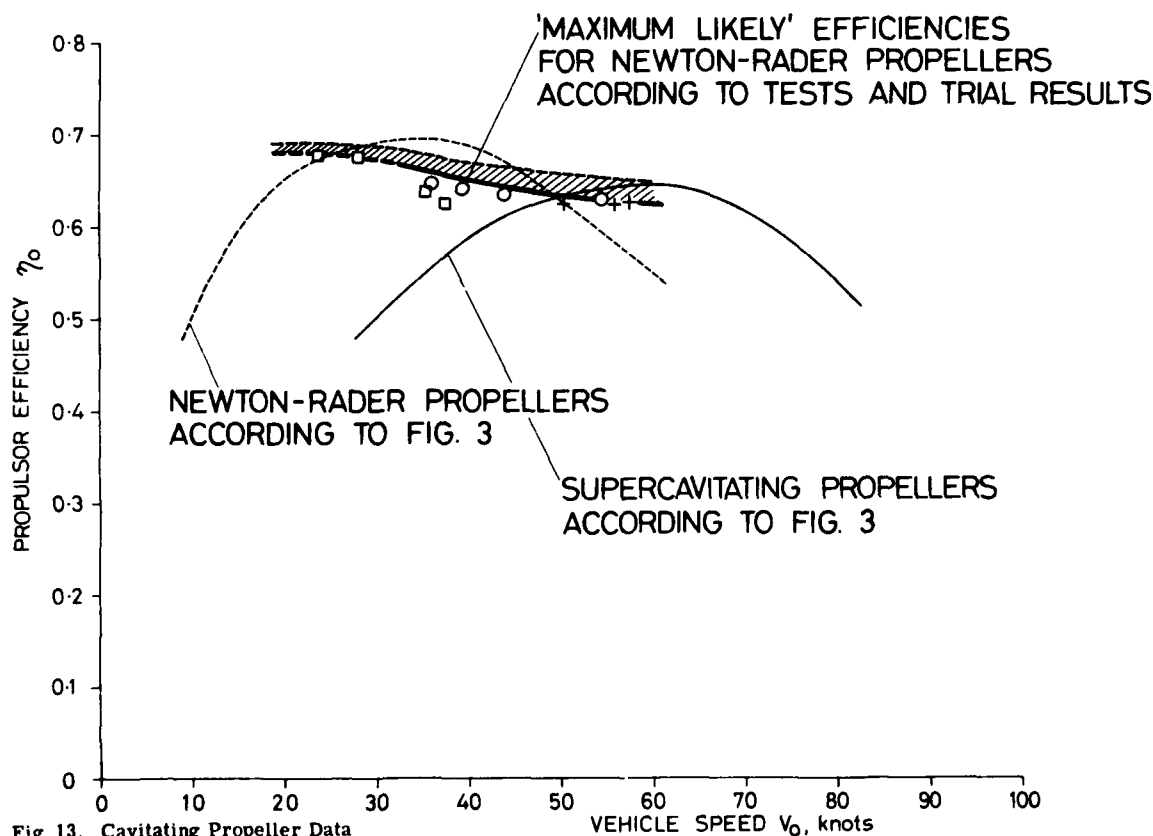

Fig. 13. Cavitating Propeller Data

My final point concerns Fig. 4. I have been trying to identify the advanced naval vehicle represented by the rhombus located towards the lower righthand corner of the figure. Could this be Mr O'Neil's aerodynahydrostat?

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Mr J. D. Brackenbury, R.C.N.C. (Member): I congratulate the author on a stimulating paper. In reading the acknowledgements, you may wonder what part the Ship Department of the United Kingdom Ministry of Defence played in the NATO study, for the United Kingdom representative quoted was, unlike his colleagues from the other NATO countries, a Naval Staff man rather than a ship designer.

For the record, of the 18 international study contributions to the working paper on which the NATO study was based, the four from the United Kingdom came from the Ship Department. This Department was also deeply involved in the technical deliberations of the study and contributed to the teams engaged in the sometimes daunting editorial task of bringing together a wide range of expertise into a paper which made recommendations for the way ahead.

Having said that, it is entirely proper that the Naval Staff is seen to play a leading role in the formulation of operational requirements which recognise the potential and limitations of existing and predicted technology-always an essential early stage in the development of new designs of warships.

On a few technical points, maintenance of speed in high sea states is acknowledged by the author as an important matter, but so, of course, is maintenance of operational capability over as wide a range of speeds and headings as possible in high sea states. This is not to say that speed is not operationally important, but to reflect that it is but one of many operationally significant factors.

The author speaks of a continuing need for full-scale sea-keeping trials. I would strongly support this, and also suggest that, in addition to the fully instrumented trials with their attendant constraints on ship's programmes, costs and analysis, there is also the need for a series of much simpler trials almost ad hoc in their nature, to determine during real operational evolutions what types and levels of motions seriously affect operational capability. This is an area scant of data.

Advanced Naval Vehicles are expensive. The author recognises this, and has quite reasonably admitted that the costs which can be operationally justified to obtain the performance features that an advanced naval vehicle provides have not been addressed in this paper. In this connection it is encouraging to see that, in addition to the more glamorous and exotic vessels which have been considered, some very sensible attention has been given to the way in which the performance features of conventional displacement forms can be enhanced, for example, by a disciplined approach to increasing their size. When weapons payloads are expensive and vehicle costs represent a relatively small fraction of the total system cost, this makes good sense, but it will require considerable discipline by the designers and the Naval Staff alike to ensure that this size increase is used for its intended purpose and not packed out with more expensive payload.

Mr W. C. E. Nethercote, B.Eng., M.Sc. (Member): I would like to raise questions about two points of detail in the author's paper.

First consider transport efficiency, which I prefer to regard as qualified lift/drag ratio. In practice, any designer of advanced naval vehicles or other types must compete against conventional types, and where concept exploration is employed it may be tempting to employ optimisation based on

Ω_0; however, such optimisation, for the SWATH type at least, will tend to drive up displacement, possibly to the detriment of promotion of the type. Would the author care to comment? Should Ω_0 be regarded merely as an illustrative tool?

Second, in summation of special features, the author noted that hydrofoils required disproportionately deep draught or size unless foils were retractable. That this may be misleading is best illustrated by reference to PEGASUS which grounded at speed during transition from foil to hull-borne mode in avoidance of a collision. It is no consolation to say that hull-borne operation was possible in the surrounding waters if it is noted that retraction of the foils could only be achieved in the hull-borne mode.

Mr A. L. Dorey, B.Sc. (Fellow): Mr Eames and his study team have certainly covered a wide range of possible craft, and I have failed to think of a type which has not been considered.

It would perhaps be expected that future development of any one of these craft will be carried out by, or on behalf of, one of the large NATO Navies, but as the paper emphasises, the conventional 'destroyer' form is hard to beat, particularly in open ocean conditions. Therefore the more restricted waters in which many of the world's smaller navies operate may produce the incentive to use less conventional craft. The paper will greatly help such navies to see the advantages and disadvantages of considering a particular type of vehicle. The present use of hovercraft in the Middle East is illustrative of this point.

Mr J. A. Sadden, R.C.N.C. (Member): The author is to be thanked for this useful paper. However I would like to seek a little more information even though security considerations may prevent anything but a very general answer.

The paper goes a long way towards answering the question of which type of vessel is best for which role. Unfortunately though, there is one piece of information which is missing, and this concerns payloads. It almost appears in Fig. 4 in the guise of transport efficiency, but unfortunately this figure relates to the deep displacement, or total weight, rather than the weight of the payload that is actually required to be carried around the ocean. It may be possible to derive payload fractions from Figs. 8 and 10 and the related tables although I suspect the weights quoted may not cover auxiliary systems.

The author refers to payload more directly in Section 7 and talks about certain ships only having useful payload fractions in certain ranges. Perhaps the author could define what he considers a useful payload fraction to be, so that we can better understand his remark that the SWATH ship will show to best advantage in the 10,000 to 15,000 t class. (I assume that he actually means 10,000 to 15,000 t total weight and not 10,000 to 15,000 t payload!).

It would be very helpful if the author could expand on this subject in his reply to the discussion.

The President then proposed a vote of thanks to the author which was carried with acclamation.

WRITTEN DISCUSSION

Captain Robert J. Johnston, U.S.N.R. (Ret.): In commenting on Michael C. Eames' paper I shall limit my discussion to hydrofoil ships. My technical association with the author has been in this particular field covering a number of pleasant years. While we have generally agreed on most aspects of the hydrofoil concepts, there have been enough areas of discussion to keep the relationship interesting and continuing. My congratulations to the author for another contribution to the development of the understanding of advanced marine vehicles.

First, I should like to comment on hullborne characteristics, particularly as they apply to military hydrofoils. Experience

is showing us that military hydrofoils spend the major portion of their operating time hullborne. USS PEGASUS (PHM-1), since delivery, has spent 61% of its operational time hullborne. Furthermore, one of the more critical aspects of extended hydrofoil operations is the distance a hydrofoil can be deployed from its source of fuel. Hullborne range is therefore a critical issue. In addition, several hydrofoils designed to date have exhibited hullborne speed gaps, that is, speeds at which continued operation is impracticable. These gaps can be overcome by operating at a combination of hullborne and foilborne speeds to achieve the average speed of advance desired. Generally when operating in this combined mode, a low range bucket is exhibited in the speed-range curve. The lowest range generally occurs just below take-off speed. This same characteristic can be observed even in some designs which do not have operational speed gaps. Recent USN design studies, in the 500 to 2400 ton displacement size, have addressed the hullborne characteristics. These studies have shown that the bucket in the range-speed curve can be eliminated along with operational speed gaps. This has been achieved by introducing fine displacement hulls. In addition, as the author points out, the compatibility of the foil configuration and the propulsion system becomes a major consideration in meeting desired hullborne operational requirements.

In this latter regard, US Navy's recent design studies track quite closely the specific machinery weights indicated by the author in Table V. For the 500 ton to 2500 ton hydrofoil designs, mentioned above, the specific machinery weights have varied from 3·5 lb SHP to about 4·5 lb/SHP (2·1 kg/kw to 2·7 kg/kw). The lower specific weights have been achieved through imaginative combinations of propulsion plants to minimise the number of transmission elements. These combinations also can result in the elimination of the hydrofoil speed gap. The indicated reduction in Table V of specific machinery weight through the use of a fixed foil system as compared with retractable foils is noted with interest.

In reviewing both the author's 'Summary of Promising Concepts' as related to the hydrofoil and the comments in this discussion, an observation is apparent. In addressing the technical issues on hydrofoils we are dealing from a base of proven, demonstrated facts. Objectives for the future are related to improvements in detail not conceptual realisation. Hydrofoil technology has a degree of maturity. We watch with interest the expansion of utilisation that has been forthcoming from the operational experience of the USS PEGASUS (PHM-1) with our fleet. This experience shows that hydrofoils can be maintained and operated by Navy personnel. In addition the military utilisation of the PHM continues to grow. It can be safely predicted that the PHM squadron introduction will result in an even further expansion of the mission and roles. Other advance ship concepts acceptability will follow as the operators learn and understand the usefulness and effectiveness of those new dimensions in naval capabilities.

Professor P. Mandel, B.Sc. (Fellow): This paper is one of a very few presented in the open literature that treats, comprehensively, all of the competitive, advanced vehicle types in an objective manner. The emphasis on maintenance of speed in sea states and not just on attainment of high calm water speed is one example of the excellent balance achieved by the paper as a whole.

This discusser was commissioned in 1974 to carry out a detailed quantitative assessment of advanced vehicles which was completed in 1977[35]. In contrast to the subject paper, we were not able to treat seaway performance in that study but the calm water results of the 1977 report lend quantitative validity to the results presented in this paper. The 1977 report treated all of the Category A 'Advanced Displacement Ships and Advanced Naval Vehicles' of Table I except for the 'Enlarged Ship'. Advanced structural, power plant and other subsystem technologies were assumed for all vehicles. The vehicles were assessed in terms of maximum speed, V, range, R at cruise speed, V_c, payload mass density, ρ_p, initial

acquisition cost, AC and annual operating cost, OC (1976 $)* for fixed selected values of vehicle mass, M_v, payload mass fraction. M_p, and installed power, P_i. For each combination of selected values, vehicle feasibility was checked in terms of allowable speeds**, weight balance, volume balance, static stability***, and availability of suitable propulsor.

Table VI summarises results for all feasible Category A vehicles as well as lighter-than-air vehicles. These acronyms are used to identify the vehicle types in the table: Conventional ship, SUR1; slender ship (length/beam ratio = 18) SUR2, SWATH ship, SUR3, semi-planing ship, PLA, fixed foil hydrofoil ship, HYD, surface effect ship (length/beam ratio = 2) SES1, surface effect ship (length/beam ratio = 6·5) SES2, air cushion vehicle, ACV and lighter-than-air ships, LTA. The absence of a vehicle in Table VI means that the vehicle is infeasible for the stated values of M_v, M_p and P_i because of one or more of the reasons given in the previous paragraph.

The major conclusions from Table VI are as follows:

(i) In the size and speed range of current large destroyers, the high length-beam SES may offer more speed but at the penalty of severe reductions in range and increased operating cost for equal acquisition cost compared to the conventional ship. In a much less pronounced manner, the slender ship offers the same advantages and disadvantages as the SES.

(ii) Also in the size range of 500-2,000 tonnes and for equal acquisition cost, no single surface vehicle type is simultaneously most outstanding in terms of both speed and range. For example, for a $8·35 × 10⁶ acquisition cost, the 500 tonne SES1 has a speed of 53 knots and a range of 1,680 miles, whereas the SUR1 is 34% slower but can go 32% further.

(iii) Even overlooking its outstanding performance in a seaway, the hydrofoil is an outstanding surface vehicle in the 100 tonne size in terms of its speed.

(iv) As is well known, the lighter-than-air ship outperforms greatly all of its surface competitors in terms of the performance features enumerated in the table.

These conclusions are in accord with those of the paper.

REFERENCE

35. Report of MIT Vehicle Technical Assessment Project, MIT Dept. of Ocean Engineering Report No. 77-14, July 1977.

Mr I. F. Glen (Member): The author is to be commended, not only on the quality of his paper, but also for the leadership and organisational capability demonstrated during the NATO Long-Term Scientific Study, the findings of which are summarised in this paper.

The concept of an 'enlarged' ship in which seakeeping ability is enhanced, not by the addition of foil or hover systems but simply by more hull, is an interesting one and hinges on the assumption that steelwork is inexpensive relative to other ship systems. This assumption is questionable, at least

* OC includes the cost of personnel to operate the ship and its own essential subsystems but not the personnel needed to operate its payload. Fuel costs were based on a 200 operating day year at a speed of 20 kts (96000 NM/year.

** All hydrofoil ships employ subcavitating foils hence they were constrained to a maximum speed of 50 knots. Maximum treated speed for other vehicles was 100 knots.

*** To be feasible, all ships, planing and hydrofoil vehicles had to achieve a specified value of metacentric height with the payload located at the baseline. For feasible vehicles, the maximum allowable height of the centre of gravity of the payload, z_p (as a fraction of vehicle hull depth, D) that meets the specified metacentric height is given as output.

currently, in Canadian yards, as steel and associated material and labour prices soar. Even if one accepts the suggestion that the initial construction cost of such a vessel may be less than the 'equivalent' SES or hydrofoil, how are the running costs affected by the lengthened hull? Certainly if endurance cruising speeds are to be held at their current levels, there may be some considerable penalty in fuel consumption with the extra long hull. Finally of course, there is the practical problem of maintaining the 'unusable volume' as void space. The concept suggests a much smaller payload, displacement ratio than conventional ships, and performance will clearly fall off rapidly if the extra volume created by the enlarged hull is used. Some suitably inert poison gas may be the only means for keeping enthusiastic operators and naval staff out

of these spaces! As suggested by the author, further exploration of the idea is warranted.

Once more, the potential of the hydrofoil as a small ocean going craft with superior size-for-size seakeeping is demonstrated, yet progress in this area is slow. Clearly the cost of current small military hydrofoils when extrapolated to larger craft is too much for the strongest naval or political stomachs, yet as the author says, we see the smaller, less sophisticated surface piercing craft operating successfully as ferries. What is the penalty, in terms of reduced payload capability, of developing the larger hydrofoil craft from the 'shipbuilding' technology base rather than the 'aircraft' technology base which appears to have been the method with

TABLE VI. Characteristics of Advanced Vehicles

M_v	M_p'	P_i	Vehicle	V	R	V_c	ρ_p	AC*	OC	z_p D
tonnes		HP		kts	NM	kts	kg/m³	$10^6$$	$10^6$$	-
100	0·20	2500	LTA	68	2570	50	23	1·40	0·64	
			HYD	40	690	40	113		0·76	1·8
			SUR1	27	1060	20	215		0·79	1·0
			SUR3	25	560	20	52		0·83	0·5**
			PLA	23	710	20	102		0·87	6·4
		5000	LTA	86	2310	50	23	2·75	0·64	
			ACV	44	20	44	46		0·85	
			PLA	34	620	20	156		0·90	6·4
			SUR3	33	440	20	63		0·84	0·5**
500		15000	LTA	86	4020	50	23	8·35	1·33	
			SES1	53	1680	50	137		2·15	
			SES2	51	1850	30	127		2·09	
			HYD	48	1160	40	181		2·19	1·9
			SUR1	35	2210	20	154		2·04	1·1
			SUR3	33	1200	20	84		2·32	1·3
			PLA	30	1510	20	155		2·34	2·6
		40000	ACV	91	710	70	160	21·8	2·36	
			SES1	91	740	60	124		2·33	
			SES2	79	740	40	99		2·34	
			PLA	53	760	20	196		2·63	6·5
			SUR3	48	760	20	188		2·50	1·5
1000		30000	SES2	56	2560	30	287	16·7	3·19	
			SES1	54	1970	54	126		3·35	
			HYD	49	1340	40	159		3·47	4·6
			SUR2	44	3060	20	136		3·00	0·3**
			SUR1	38	3390	20	255		2·99	1·3
			SUR3	36	1850	20	132		3·45	1·7
			PLA	31	2090	20	259		3·55	2·8
		60000	ACV	87	1110	80	82	32·8	3·56	
			SES1	84	1060	60	82		3·56	
			SES2	77	1560	40	220		3·46	
			SUR2	58	2430	20	303		3·13	0·3**
			PLA	49	1560	20	287		3·57	2·7
			SUR3	46	1380	20	276		3·65	1·7
2000		60000	SES2	60	3100	40	239	33·5	4·88	
			SES1	55	2640	55	265		5·19	
			HYD	50	1470	50	144		5·55	4·8
			SUR2	48	3930	20	126		4·49	0·5**
			SUR1	41	4690	20	221		4·39	1·4
			SUR3	39	2640	20	122		4·96	2·2
5000		80000	SES2	48	4970	40	151	45·0	8·21	
			SUR2	42	6880	20	143		7·48	0·8
			SUR1	35	7960	20	144		7·22	1·6
			SUR3	31	5440	20	206		8·00	2·8
10000		100000	SUR2	38	10060	20	174	58·0	11·00	1·1
			SES2	38	6630	38	129		12·32	
			SUR1	34	12290	20	176		10·47	1·9
			SUR3	28	6160	20	169		12·76	3·1

* Grossly estimated as a function of vehicle mass and installed power
** Dubiously feasible vehicle

military hydrofoils to date? The author's comments in this area could be of value.

Once more congratulations to the author for a paper which will serve as a useful reference to the state-of-the-art and a pointer to the future for those with an interest in Advanced Naval Vehicles.

Dott. Ing. L. Rodriquez (Fellow): Fig. 3 shows efficiency envelopes for various propulsors. Whilst I agree on the qualitative aspect highlighted by the diagram, I find that some numerical values are rather questionable.

Navaltecnica's (now Rodriquez Cantiere Navale S.p.A.) latest surface-piercing hydrofoil craft, the RHS 200, is provided with controllable pitch super-cavitating propellers, having a designed efficiency of 0·687, at a cruising speed of 37·5 knots, whereas the diagram gives a maximum value of about 0·57.

On the other hand, Myers[36], presented a similar diagram with remarkably different values for subcavitating propellers. In my opinion, this is a confirmation that curves of this kind, although very useful for an overall view, may sometimes lead to inappropriate conclusions.

The author's opinion on the aforementioned discrepancy, as well as some information about the way data were collected to compile this diagram, would be very much appreciated.

I do agree about the need for standard criteria of evaluation and presentation of seakeeping results. In this regard, my personal feeling is that seakeeping should be looked at from the point of view of the crew task performance, once due consideration has been given, of course, to structural loadings and propulsive capability in extreme conditions. A leading track in this field in perhaps already traced, as it is now widely accepted that the parameter governing crew task performance is vertical acceleration together with its fundamental frequency and the time of exposure.

Therefore, representing the aforementioned parameters, for example, in terms of RMS g values at a standard reference point vs peak frequency at several frequencies of encounter, would allow comparison between the performance of a marine vehicle and boundaries of human tolerance, such as ISO 2631, Ref. 37, or Shoenberger's curves, Ref. 38. This would be a relatively simple way of assessing seakeeping data and contemporarily it would be the starting point for studying the way a stabilisation system has to work in order to improve the ride of a given vehicle.

A final observation concerns the data representation of Figs. 5 to 7. I find it desirable that such curves be shown with some indication of the criteria adopted, if any, for determining the loss of speed.

A suitable criterion, in my opinion, was suggested by Chaplin, Ref. 39, and by Di Blasi, Ref. 40, who assume RMS vertical acceleration as a parameter for plotting curves of speed vs wave height. Such a representation, although requiring a large collection of data, has the advantage of defining clearly the conditions which affect sea speed.

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Mr T. K. S. Murthy, M.A., M.Sc., Ph.D. (Member): The author is to be congratulated on his presentation of an excellent paper containing the concerted views of some 35 technical experts from seven different countries regarding the technological advances contributing to high-speed ship design in the future.

I have one reservation, however, and this is from a purely personal aspect. This relates to my Semi-Submerged Air Cushion Vehicle (SSACV) concept (UK Patent Specification No. 1475084) which has been overlooked in this paper although it has been widely presented in the USA, Canada and in Europe on several occasions during the last four or five years and most recently (March 1979) to the IEG/6 Committee of the NATO Defence Research Group in Brussels. Some technical documents featuring this concept were supplied to the author a couple of years ago, but he has apparently thought fit not to make any such mention in his otherwise exhaustive study of the available options for higher speed at sea. The SSACV concept combines the aerostatic lift of the air cushion with the hydrostatic buoyancy of a pair of submerged hulls and would therefore lie along the line XZ of Fig. 11. In other words, the SSACV is simply a SWATH ship with an air cushion or, alternatively, an SES with submerged hulls below the side struts.

A preliminary study of the performance of a 4, 000-tonne SSACV was completed in August 1978 for the French Ministry of Defence under contract and a copy of the report, cleared by the French authorities for publication, has recently been supplied to the author after the presentation of the paper. This theoretical study has yielded some very interesting and promising results for a high-speed marine vehicle for tactical operations and there is also a clear enumeration in the report of the superior advantages of the SSACV over the SWATH ship. To mention one example, the author has drawn attention to the disadvantage of the SWATH ship design in Section 7.2 in respect of its weight sensitivity on account of the very small reserve buoyancy. This does not apply to the SSACV as the air cushion is capable of providing adequate heave stiffness supplementing the possibly small amount of tons per inch of the immersed part of the side struts. There are also several other advantages.

Perhaps the author would be good enough to briefly comment on the viability of the SSACV concept for the purpose on hand in his written reply.

Mr K. J. MacCallum, B.Sc., Ph.D. (Member): This paper has been most enjoyable, providing a good insight into current development in warship designs and focussing our attention on areas for research. The reader, however, is intrigued by the comments in Section 1.3.3 on the 'enlarged ship'.

The paper says that this concept will be unpopular. There is a suggestion here that the objectives of warship design are not always clearly stated and that there is not an adequate definition of the measures of merit which will be used in the evaluation of different designs. It is unlikely that this is the case, and some of the factors involved are suggested in Section 7.

Nonetheless, it might be of some value if the author could comment on this aspect of design. How are objectives defined, and what criteria are used? Is use made of computer based optimisation, or multi-criterial evaluation techniques?

Professor J. P. Kundu, B.E., B.Tech. (Member): The author has defined Transport Efficiency (Section 2.3) as $C \cdot \dfrac{\Delta V_0}{P_0}$.

Transport means 'to carry', 'to convey'. In the expression, Δ represents the total weight of the ship and not the weight carried by it. Indeed the items of the expression are more related to the movement of the ship as a whole and its power. Perhaps a term like 'movement-power ratio' (or any other

similar term) would have been more appropriate than Transport Efficiency.

The efficiency of a machine or a plant is not more than unity, but as defined the Transport Efficiency has worked out much more than unity (Fig. 4). This perhaps sounds somewhat confusing. If the suggested term (or any other suitable term) is accepted, the ambiguity could be eliminated.

In Fig. 4 the author has shown curves of Transport Efficiency (dotted lines) for existing naval vessels of various types and has also forecast such efficiency lines (full lines) for them. However, it is noted that no such forecast for Planing Craft and Surface-Effect Ships (SES) has been made; or it could be said that their forecast curves coincide with those of the existing Planing Craft and SESs. Is it to be concluded that no further improvement in Transport Efficiency of these two types of vessels can be visualised ?

In Fig. 10 both the ordinates have been graduated with installed power per ton of displacement (one in metric and the other in Imperial units). Perhaps one ordinate could have been used to represent the expected speed ranges for typical warships (with 5-15 kW/t) and also for ANVs (with 30-80 kW/t).

Under the heading 'Summary of Special Operational Features' (Section 7.5) the author has put forward the various points for and against (hydrodynamic and operational) various types of ANVs. Perhaps one more point on the economic aspect (e.g. running cost per 100 sea-miles) of each type of vessel would have provided useful and important information for readers.

AUTHOR'S REPLY

Introduction

An overall impression I gain from the valuable and interesting discussion is that, in my drastic condensation of this broad study, I did not place enough emphasis on its scope and purpose. The words are there, but their significance has been missed by several contributors.

The true worth of a warship cannot be defined within the traditional scope of naval architecture. Combat-systems engineering plays at least an equal role in design, and in most cases the dominant role. Moreover, design is essentially responsive to operational requirements, as determined from forecasts of the threat to be faced in the specific tasks foreseen. Naval architecture occupies but one corner in the triangle of disciplines involved in defining a warship.

As explained in the opening summary, this paper deals only with forecast advances within the field of naval architecture, or the design of the ship's 'platform'. In recent years, several new types of platform have emerged so that, in addition to forecasting technological advances by discipline, a second objective of this NATO study was an unbiased assessment of what these platform concepts offer the future warship designer. Clearly one cannot predict their military value from platform considerations alone and, most emphatically, there is no attempt here to 'sell' any of the 'advanced naval vehicles' (ANV).

Indeed, a problem with most current literature on ANVs is that these future ship types are usually compared against existing warships, which were obviously designed many years ago. An important aspect of the NATO study is that it assessed what advances can be foreseen in conventional platform design over the same time scale. Only by assuming comparable levels of technology applied to displacement ships can we hope to obtain valid comparisons of platform potential.

The final objective of the NATO study was to recommend priorities for research and development, and this is very different from recommending any specific choice of platform. To re-quote a final conclusion, no single type of vehicle will prove to be universally superior. Each has different per-

formance characteristics which will vary in importance according to the tasks to be performed and the military payload to be carried.

Topics beyond scope

I am afraid that I have to disappoint Dr Baxter, Mr Brown, Mr Jackson, Mr Brackenbury, Mr Sadden and Dr MacCallum, who have raised questions beyond the scope and purpose of the study. Their contributions are valuable, but the answers to their questions—asked or implied—lie in studies yet to be completed, as I am sure they appreciate.

Because of this, I would take issue with a conclusion drawn, prematurely I believe, by Dr Baxter. While it is very true that the size and weight of electronic equipment required to be carried is still growing, we have to remember that operationally-proven combat systems lag several years behind the state of the electronics art. The full impact of micro-electronic technology has yet to be felt by the naval architect, and it is not at all clear that the current growth need continue unabated. I say *need* continue because it *will* continue if naval architects can find the space and governments can pay the bills for additional 'goodies'. But it does not necessarily follow that the limited payload capacity of most ANVs will continue to be a severe constraint to their use by the blue-water navies. Some current design concepts are already acceptable in terms of capability; it is the risks and costs that are daunting.

This trend for acceptable capability to be practical in smaller sizes of vehicle may eventually modify the point raised by Mr Dorey, although there is much truth in what he says today.

Mr Brown asks if I can indicate the relative cost per tonne of various craft, but this can be dangerously misleading. I can say that the cost of an ANV *platform* per tonne is 3 to 5 times the cost per tonne of a conventional platform, but what does that mean? Platform cost may be less than half the total acquisition cost of a ship, and is but a small fraction of the life-cycle cost. These fractions vary greatly with the size and type and with the combat systems installed. Moreover, only a fraction of the number of platform tonnes is needed to do the equivalent job with an ANV, particularly because of their very low density. So the true answer is that I cannot indicate costs in a way that is meaningful.

Resistance and propulsion

Having opened the meat of the paper with Professor Mandel's earlier work on calm-water performance, I was delighted to have his latest contribution adding to the value of the paper. As he says, his results lend support to our conclusions. They also support Dr Baxter's suggestion that 40 knots might be regarded as a crude dividing line between the zones of promise of advanced displacement ships and ANVs. It is dangerous to generalise, however; an ANV may show special advantages for some roles at lower speed. For others it may be preferable to drive a displacement ship beyond 40 knots, and I am not aware of consciously stressing this figure.

For the reasons expressed above, I rather wish that Professor Mandel had omitted his columns of cost estimates, but I suppose I should thank him for taking me off Mr Brown's hook!

I share Professor Kundu's and Mr Nethercote's dislike of the term 'transport efficiency' and plead guilty to accepting the most common terminology. This parameter is the product of lift/drag ratio (Δ/R) and overall propulsive efficiency (η). As an illustrative tool it has the great practical advantage that data on displacement, power and calm-water speed are most readily available.

I agree that it is not a good parameter for optimisation. In the NATO study we defined a 'Useful Transport Efficiency' (effectiveness would be a better word) which is the product of transport efficiency (as defined in the paper), payload ratio (W_u/Δ) and sea-speed ratio (V_w/V_o). Hence,

$$U.T.E. = \Omega_{uw} = 5.045 \frac{W_u V_w}{P_0} \frac{(t)(kt)}{(kW)} = 6.878 \frac{W_u V_w}{P_0} \frac{(ton)(kt)}{(HP)}$$

This is as good a performance indicator as I have found, if one must have a single figure. Personally, I prefer to investigate the effect of each of the product terms separately.

In reply to Professor Kundu's query, the reason that no dotted lines appear in Fig. 4 for planing craft and SES is that we expect the trend of their future development to be in the direction of improved seakeeping, possibly even at the expense of calm-water performance. He has misinterpreted the diagram. The forecasts are made (solid lines), it is the 'current best' lines that are omitted.

I am sorry to disappoint Mr Jackson, but the diamond in Fig. 4 is a proof-reading goof, not Bill O'Neill's aerodynahvdrostat. Cancellation of an erroneous planing-craft spot was interpreted by the tracer as a diamond. It would indeed have been a 'gem' among planing craft.

I am grateful to Mr Suhrbier for his valuable information on the Newton-Radar type of propeller, and it is encouraging to see the wide speed range predicted for this type. I fear that both he and Dr Rodriquez are leading more into this diagram than was intended. As Dr Rodriquez points out, such a presentation can only be regarded as an illustrative overall view.

The effect of Mr Suhrbier's contribution is to suggest that we should drop the term 'transcavitating propeller' and merge its curve with that shown for the supercavitating propeller, to produce one broader envelope for propellers designed to operate under cavitating conditions. I agree with this and it solves the sort of semantic problems Dr Rodriquez finds with the sample propeller he quotes. At 37·5 knots an efficiency approaching 0·7 can certainly be predicted for a cavitating propeller; whether or not it is truly supercavitating is probably an unimportant question of definitions.

Seakeeping

Dr Rodriquez, Mr Brackenbury and Dr Baxter support our plea for seakeeping criteria which take into account the degradation of crew task performance and other aspects of operational capability. I am pleased to be able to say that the whole subject of seakeeping criteria is now being pursued very actively on a multi-national basis within NATO.

Dr Rodriquez's contribution is most interesting and I agree with much that he says. However, I would caution against oversimplification. The effects of vertical acceleration are not always those that govern crew task performance. In BRAS D'OR, for example[17], we found that a mild lateral acceleration could prove more disconcerting to the crew than much higher levels of vertical acceleration.

Mr Brown is drawing an unjustified conclusion from Figs. 5, 6 and 7. These curves are intended to illustrate the expected speed losses and how different these are for the various vehicle types. The initial calm water speeds were selected to represent typical examples, and the sample SES is clearly of the high-speed, low-L/B type such as the USN's 3KSES proposal. This does not constitute a forecast that all SES and ACV will be designed for the same speed; clearly the high-L/B type of SES is better suited to more modest speeds, as he suggests.

Structures

I cannot agree with Professor Faulkner when he says that the structural weight fraction of destroyer types is fairly constant. The data in Fig. 8 show destroyer values from 0·23 to 0·38, depending on vehicle density as one would expect. However, on the more important issue I think we are in closer agreement than he suggests. Fig. 8 confirms that naval displacement ships show a wide scatter of 'structural efficiency', and we strongly advocate the application of improved design methods to reduce this scatter.

Nevertheless, it is fair to predict that such methods are unlikely to improve significantly on the *best* warship designs existing today. Improved methods will lead to consistency, but not to a significant decrease in structural weight fractions below the lowest shown in Fig. 8 (close to the 80 kg/m³ structural density line). Moreover, as Professor Faulkner suggests, there may be valid reasons for not seeking the absolute minimum value. Thus we believe that the region dotted in Fig. 8 will remain valid in the foreseeable future.

There may well be scope for significant structural weight reduction in large merchant ships. This is not addressed in the paper and I am not qualified to comment.

Professor Faulkner also raises the question of hydroelastic instability of hydrofoil systems. Flutter has certainly been investigated in model tests, and an early design of central main foil for BRAS D'OR was modified because it appeared uncomfortably close to the flutter boundary at 60 knots, but I know of no full-scale experience of flutter.

Our rejection of composite materials having a low modulus was more generally based on the difficulty of handling large deflections in foils and struts. Consider, for example, the alignment of propeller shafts within deflecting struts, or flap hinges along the trailing edge of foils.

To Dr Baxter's very broad question on the future use of aluminium or other materials in place of steel, there is really nothing I can usefully add to the answers given in the paper: in Section 4.1 generally, and in Section 4.3 for specific ship types.

Mr Brown suggests that the use of copper-nickel cladding for anti-fouling seems contrary to 'my light-weight philosophy'. I hope I have not given the impression that light-weight should be a paramount philosophy for all types of ships. On the contrary, a major thesis of the study is that the advanced engineering needed to achieve the light weight essential to an ANV may not be justified by the operational need. Clearly one should not waste weight in any ship, but the advanced displacement ships do not have the same motivation for costly weight reduction.

Power plants

Dr Baxter asks for my views on the advantages of CODOG installations as the price of fuel increases. It is difficult enough to make technological predictions; economic forecasts can only be wild guesses. A point made in the paper is that this issue is not as clear cut as it seems today, because the fuel economy of gas turbines is likely to improve at a much faster rate than that of diesels. These trends are demonstrated in Fig. 9 in a way that carefully dodges the issue of oil prices! Whether or not this expected reduction in the fuel-cost difference will be enough to justify the operational advantages of gas turbines will depend upon the rate of oil price rise, and the significance of fuel costs in the total life-cycle cost of a particular design.

To inject a purely personal opinion, not attributable to the NATO study, I think that economics may well dictate a new concept of separate 'peacetime' and 'wartime' engines being installed in ships. Perceptions of cost and value differ radically in peace and war, and with them the operational need for speed. CODOGAG installations may soon be with us, but I hope we will invent a better name for them.

I was pleased to have Captain Johnston's confirmation of the specific machinery weights suggested in Table V. Because the major influence of non-retractable foils is to reduce the number of transmission elements, our agreement is even closer than he suggests.

I am afraid I do not follow Professor Kundu's suggestion in regard to Fig. 10. The factor linking power per tonne with speed is the 'transport efficiency', which is hardly a constant of proportionality, even for a specific vehicle type. The purpose of this diagram is to show the trends of machinery weight fraction.

SWATH ships

I find Mr Brown's comments on SWATH ships somewhat contradictory. I agree whole-heartedly that a SWATH should not be designed with an emphasis on light-weight. Provided it is sufficiently large, it becomes essentially a displacement ship of different shape, with no need for advanced engineering. However, because of the large structural weight fraction inevitably associated with this different shape (see Fig. 8), it is difficult to achieve acceptable payloads in small sizes. Just how much constitutes an acceptable payload ratio varies widely with the envisaged role, and this probably accounts for Mr Brown's different minimum practical size. (I am sorry Mr Sadden, but I cannot be specific).

For example, we find it difficult to design a competitive SWATH frigate under about 5,000 tons. At this size the platform cost is about 10% higher than for a conventional ship, and I do agree with Mr Brown that the first operational class of SWATH ships likely to evolve (other than for limited special roles) will be in the 5,000 tons size range.

Mr Brown gives no details of his 1300-1500 tons offshore patrol vessel, but if it cost about twice as much as its conventional counterpart, it is not just a conventional ship of different shape. Doesn't this cost suggest that it is too small to be a practical contender?

The reason for suggesting that SWATH ships will show to best advantage in the 10,000-15,000 ton class is simply that here is where their unique advantages for operating aircraft come to the fore. Such ships would have adequate flight-deck proportions for STOL operation, could accommodate roughly one aircraft per 1,000 tons, and would have the motion characteristics of carriers in the 30,000-45,000 ton class. This combination of features is thought to open the door to reasonably priced aircraft carriers for the smaller NATO navies.

Hybrids

A great variety of speculative vehicle concepts was examined in the NATO study. If Dr Murthy reads carefully, he will find none of them identified by the name of its originator. (Too often a prior originator turns up, who simply did not think his idea worth patenting). I fail to see why Dr Murthy should expect unique treatment. We are concerned here with the promise of concepts, and his SSACV is an air cushion/buoyancy hybrid, discussed in Section 6.1.1. We did not find it promising.

If, following Dr Murthy, we define σ to be the fraction of the total weight of an SSACV carried by the air cushion, we found that power requirements were least up to a speed of about 60 knots when $\sigma = 0$, i.e. when the SSACV is a SWATH. Beyond this speed, the largest values of σ required the least power, i.e. when the SSACV is an SES.

In regard to seakeeping, the SWATH is clearly superior. At speeds beyond SWATH capabilities no meaningful assessment could be made, but so little wetted area can be tolerated at these speeds that one could not expect substantial differences between the SSACV and the SES.

A major attraction of buoyancy-*hydrofoil* hybrids is that, by sharing the load, larger sizes can be contemplated within practical foil loadings. An air-cushion is not size limited in the same way, and since the practical speed regimes of SWATH ships and SES overlap, there is little motivation for the complexity of a hybrid.

In his discussion, Dr Murthy suggests that the air cushion of an SSACV can be used to supplement the tons-per-inch of the SWATH. Low TPI is fundamental to the excellent seakeeping of SWATH and to suggest compromising this primary attribute to solve a secondary design problem is curious logic indeed.

Hydrofoil ships

Captain Johnston's report on recent experience with USN hydrofoils is a valuable addition, clearly bringing home his point that hydrofoil technology has achieved a degree of maturity not yet possessed by the other ANV types. I was particularly interested in his explanation of the increased attention the USN is now paying to hullborne characteristics. Knowing the position I have taken on this in the past, he will be picturing my smile of satisfaction!

Mr Nethercote makes a valid point about draught requirements with retractable foils. It remains true, however, that foil retraction obviates the need for deep-water berthing facilities. I will resist the temptation to comment further on fixed foils versus retractable foils, especially since Captain Johnston has said such nice things.

Mr Glen raises a very significant issue. Most existing hydrofoil craft fall into two categories; the European commercial types, with fixed, surface-piercing foils, diesel engines and straight-drive shafts, and with structure and outfit following marine practice; the US types, with retractable, fully-submerged foils, gas turbines and Z-drive transmissions, and based more closely on aeronautical practice. There seems to be no fundamental reason why all of these features should be grouped the way they are. There should now be sufficient maturity of design knowledge to select the features really needed for a specific operational requirement, probably emerging with 'intermediate' types that would also be intermediate in cost.

I cannot answer Mr Glen, because such studies have yet to be done, but I anticipate that an 'intermediate' hydrofoil developed from the shipbuilding technology base, using fixed, fully-submerged foils, could meet significant naval requirements with less risk and lower cost than the fully sophisticated US type. As one US designer is fond of saying wistfully, 'The European boats are no good for anything except making money'.

Enlarged ship

Moving from the exotic to the mundane, I was pleased by the reception of the enlarged ship by Dr Baxter, Mr Brackenbury and Mr Glen. I do not underestimate the practical difficulty of keeping space-hungry combat-system engineers at bay, and support Mr Glen's suggestion of poison gas!

The enlarged ship has not been studied to the depth needed to answer Mr Glen on specific costs, but I would be surprised to find this concept expensive relative to its competitors.

In reply to Dr MacCallum, my comment regarding its unpopularity was directed more at politicians than at the naval staffs. Over the past few years, much criticism has been expressed over the apparent sparsity of weapons in NATO warships compared with their Warsaw Pact counterparts. This emptiness would be even more apparent in an enlarged ship.

Concluding remark

Finally, in response to Mr Brown's request, the appended glossary of symbols is offered. In closing, I am most grateful to the 16 contributors who have added a great deal of value to the paper. I regret that the limited scope of the NATO study prevents me from providing satisfactory answers to all the intriguing questions raised. I can only hope that this sort of exposure may help to spark the additional studies that are surely needed if we are to make the most cost-effective selection of our future classes of warships.

Glossary

B   Breadth, waterline, or of air cushion

D_{WH} Wave drag at hump speed

F_H Froude number at hump speed, based on L

F_{V_0} Volumetric Froude number at maximum calm-water speed (see Table II)

L   Length, waterline or of air cushion

L/D   Lift-drag ratio = Total weight/Total resistance

P_{SO} Power installed

P_0 Power required at maximum calm-water speed

p_c Pressure of air cushion

R   Total resistance

V_0 Maximum calm-water speed

V_W Maximum sea speed in design wave height

W_h Weight of hull structure

W_m Weight of machinery installation

W_u Operational weight, i.e. military payload

Δ Total weight or full-load displacement

η Overall propulsive efficiency

η_0 Efficiency of propulsor

Ω_0 Transport efficiency (see Section 2.3)

Ω_{uw} Useful transport efficiency (see author's reply)

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This paper is a summary of some possible advances in the naval architecture of fast surface warships, as forecast for a recent NATO Long-Term Scientific Study. The forecasts cover resistance and propulsion, seakeeping, stability and control, materials and structures, and power plants, considering both conventional and unconventional hull types. They do not address any aspect of the combat systems or other outfit installed.

On the basis of these forecasts, the potential of promising types of surface warships is outlined, in so far as this is possible without specifying the function of a ship or its payload. These conclusions reflect a consensus reached by 35 experts from the seven nations participating in the NATO study.

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KEY WORDS

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WARSHIPS
SWATH
HYDROFOIL
AIR CUSHION VEHICLE
SURFACE EFFECT SHIP
HULLS
RESISTANCE
PROPULSION
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